Limit Order Placement by High-Frequency Traders

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Abstract

Using a unique dataset consisting of limit order placement, execution, and cancellations on Nasdaq, we examine liquidity provision by high-frequency trading (HFT) firms, which is a central issue in the ongoing debates about HFT. We find that HFT firms more effectively use order cancellation to strategically manage their limit orders in anticipation of short-term price movements than non-HFT firms. HFT firms increase their liquidity provision during periods of high volatility; their liquidity provision is less affected by order imbalance shocks than that of non-HFT firms. Overall, our results indicate that HFT limit orders exert a stabilizing influence on markets.

The significant growth in high-frequency trading (HFT) in recent years has led to considerable debate about its impact on market quality and wealth distribution among investors.[1] A key question is whether HFT improves market liquidity (Jones 2013). Researchers generally report that HFT improves market quality by narrowing bid-ask spreads (Jovanovic and Menkveld 2011; Malinova, Park, and Riordan 2013) and supplying liquidity in transactions when spreads are wide (Carrion, 2013). Others argue that the liquidity provided by HFT is illusory and difficult to access because it is usually cancelled within an exceptionally short period of time (i.e., in milliseconds), and has been dubbed as "phantom liquidity."[2] Some researchers have focused on the liquidity-taking behavior of HFT firms, with some limited analysis on their liquidity provision during transactions (Brogaard, Hendershott, and Riordan 2014), yet few have examined the interaction between HFT liquidity providers and the limit order book (LOB) to directly address the concerns raised by the opponents of HFT.[3] An understanding about the liquidity provided by HFT firms (hereafter, HFT liquidity) via the LOB can potentially contribute much to the ongoing debate about the role played by HFT firms in modern securities

[1] In the United States, the Securities and Exchange Commission (SEC) recognizes that "by any measure, HFT is a dominant component of the current market structure and likely to affect nearly all aspects of its performance" (Securities and Exchange Commission, 2010, Release No. 34-61358; File No. S7-02-10). In 2012 the SEC expressed serious concerns about the potential impact of HFT on market quality (see, "SEC May Ticket Speeding Traders," *The Wall Street Journal*, February 23, 2012). In Europe, the latest MiFID II "will introduce specific provisions designed to ensure that high frequency trading (HFT) does not have an adverse effect on market quality or integrity." Under MiFID II, HFT firms engaging in proprietary trading need to be authorized by exchanges. See "MiFID II – What is changing," Financial Conduct Authority, September 12, 2014, available at: https://www.fca.org.uk/firms/markets/international-markets/mifid-ii/what-is-changing, accessed on July 17, 2015.

[2] See, "Concept Release on Equity Market Structure," Securities and Exchange Commission, 2010, p. 50; and "High-Frequency Trading: Background, Concerns, and Regulatory Developments," Congressional Research Service, 2014, p. 19.

[3] Some researchers examine the aggregated impact of HFT liquidity on market quality using market events that affect the trading of the high frequency market making firms (Hagstromer, Norden, and Zhang 2013; Malinova, Park, and Riordan 2013; Friederich and Payne 2015; Jovanovic and Menkveld 2015). Unlike these researchers, we examine the dynamics of HFT liquidity on the LOB.

markets.[4]

Chordia, Roll, and Subrahmanyam (2000, 2001) and Acharya and Pedersen (2005) demonstrate the importance of market liquidity. In today's securities markets, HFT firms have largely assumed the role of traditional human market makers (Menkveld 2013), so that it is especially interesting to understand how they provide liquidity via limit orders. We note that limit orders are an important source of market liquidity (Biais et al. 1995), and recent advances in trading technology have significantly reduced the costs to monitor and alter limit orders (Hasbrouck and Saar 2011; Jones 2013), making limit order trading more attractive. Jovanovic and Menkveld (2011) and Hoffman (2014) suggest that compared with non-HFT firms, HFT firms are more likely to supply liquidity via limit orders since their superior technology can reduce adverse selection risk in market making.[5] Finally, the widely-adopted maker-taker pricing by exchanges around the world provide additional incentives for traders to trade via limit orders.

In this study, we examine how HFT firms provide liquidity on the limit order book (LOB). We reconstruct the LOBs for a sample of 116 stocks traded on Nasdaq during the first quarter of 2011. Using information on 26 trading firms which are identified by Nasdaq as mainly engaging in HFT activities, we provide a detailed analysis on their liquidity provision activities via limit order placement, including executed and cancelled orders. To the best of our knowledge, such an analysis of HFT limit orders has not been conducted before.[6]

[4] Recently the European Securities and Markets Authority calls for further research to "assess the actual contribution of HFT to liquidity." See, "High-frequency trading in EU equity markets," European Securities and Markets Authority, November 1, 2014.

[5] Research has shown that in a quote driven market, specialists can be informed (Ready, 1999) due to their exclusive access to the information about floor brokers (Benveniste, Marcus, and Wilhelm 1992) and the LOB (Madhavan and Panchapagesan 2000; Harris and Panchapagesan 2005). Such privileges become less apparent when most equities markets today have an electronic LOB.

[6] Brogaard, Hendershott, and Riordan (2014) (BHR 2014) also conduct some analysis on the liquidity provision by HFT firms. Our study differs from BHR 2014 in a number of ways. First, since the data used in BHR 2014 are limited to transactions, their study focuses on the effects of liquidity-taking behavior of HFT firms. Second, the findings of BHR 2014 on the liquidity provision by HFT firms are based on limit orders executed in transactions. In

We find that the average size of HFT limit orders is smaller than that of the limit orders from other traders, whom we define as the non-HFT firms. However, the median sizes of limit orders are similar between groups. The limit order cancellation ratios are also very similar between HFT firms and non-HFT firms. The limit order execution ratios are smaller for HFT firms when we examine limit orders submitted to the top three price levels of the LOB. However, when we include all limit orders submitted to the top 50 price levels of the LOB, the order execution ratios become similar between the two groups. In general, our results show that the commonly perceived special features of HFT liquidity provision, such as smaller order size and being less accessible when needed by liquidity demanders, are not unique to HFT liquidity.

A large number of limit orders submitted and cancelled within a short period of time can increase the uncertainty of liquidity and affect wealth distribution among traders.[7] The rise of such fleeting orders is widely attributed to the increase of HFT, but there is little evidence to support this perception. We analyze this issue and find that the time that a limit order rests on the LOB is significantly shorter for the limit orders of HFT firms than for those of non-HFT firms. For stocks with large, medium, and small market capitalizations (hereafter, large-, medium-, and small-cap stocks), the median time a limit order rests at the top 50 price levels of the LOB before an execution or cancellation is 1.85, 6.02, and 18.30 seconds for HFT firms, and 4.12, 8.98, and 22.43 seconds for non-HFT firms, respectively. For limit orders submitted to the top three price

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our study, we provide a detailed analysis of the liquidity provision by HFT and non-HFT firms for all limit orders in the top 50 price levels of the LOB. As a result, the policy implications of our study complement those of BHR 2014. More recently, in another concurrent and complementary paper, Brogaard, Hendershott and Riordan (2015) examine the impact of HFT limit orders on price discovery; in contrast, our focus is on liquidity provision and we provide a more detailed analysis on the dynamics of the LOB. While our HFT classifications originate from Nasdaq, they use algorithms to classify firms as HFT firms (for an analysis of potential issues induced by classification algorithms for HFT firms, see "Equity Market Structure Literature Review Part II: High Frequency Trading", Securities and Exchange Commission, 2014).

[7] Hasbrouck (2015) documents that the volatility of quote changes at fifty millisecond intervals are about three times of the volatility measured over 27-minute intervals and the uncertainty associated with short-term liquidity provides a significant advantage to liquidity takers with faster speed. Baruch and Glosten (2013, p. 28) provide some theoretical explanations for the rationale behind the fleeting orders.

levels of the LOB, the median time to cancellation of HFT firm (non-HFT firm) limit orders is 0.53 (3.02), 2.15 (3.47), and 6.84 (4.48) seconds for large-, medium-, and small-cap stocks, respectively. These results confirm the common belief that HFT liquidity rests on the LOB for a shorter period of time than non-HFT liquidity.

In a closer examination of the distribution of limit orders across the LOB we find that HFT firms gradually reduce their liquidity on the LOB at price levels further away from the top of the LOB. Intraday analysis shows that HFTs place limit orders on the LOB exhibiting a pattern consistent with a strategic behavior of a liquidity provider in the presence of market volatility. Following Naes and Skjeltorp (2006), we further calculate the slope of the LOB for the limit orders of HFT firms and non-HFT firms and find that HFT firms strategically place more liquidity further away from the top of the LOB ahead of an increase in price volatility. Our tests on the impact of order submission and order cancellation reveal that across all stock groups, HFT firms tend to cancel buy (sell) limit orders ahead of a short-term price decrease (increase), while for non-HFT firms the relation is the opposite for large-cap stocks and significantly weaker for the medium- and small-cap stocks. Our results indicate that compared with non-HFT firms, HFT firms are more capable of using order cancellation to manage the risk of trading with limit orders, which results in their liquidity being more informed (Brogaard, Hendershott and Riordan, 2015).[8]

Liquidity providers must maintain a balance between the adverse selection costs and opportunity costs of trading. Agents incur adverse selection costs if the liquidity they provide is

[8] We find that the submission of buy (sell) limit orders is followed by an increase (decrease) in short-term prices. This effect is stronger for non-HFT firms than HFT firms. Since the total volume of limit orders submitted by non-HFT firms is significantly higher than that of HFTs firms, these results are consistent with the conjecture that limit order placement affects subsequent price movements. However, our results on price behaviors following order cancellation by HFT firms and non-HFT firms are the opposite. Given that the limit order cancellation ratios are similar between these firms, our results on order cancellation are unlikely to be driven by the same reason as the results for order submission.

taken by informed traders, and incur opportunity costs if their orders are not executed and the price subsequently moves unfavorably. We note that compared with HFT firms, non-HFT firms are more likely to trade for exogenous reasons that are not directly related to short-term stock performance.[9] For example, a mutual fund manager can trade based on fundamental analysis or execute a large order on behalf of a client. Hence, for non-HFT firms, the opportunity costs (i.e., the possibility of a failure to execute an order because the price subsequently moves away from the order), may outweigh their concerns about being adversely selected.[10] On the other hand, HFT firms are professional traders who aim to maximize trading profits. Therefore, relative to non-HFT firms, they can be more focused on the management of adverse selection risk. Thus, we hypothesize that it can be rational for non-HFT firms to purposely expose their limit orders to higher adverse selection risks if they can achieve a better execution rate in return. To test this hypothesis, we compare the opportunity costs and adverse selection costs of limit orders submitted and cancelled by HFT firms and non-HFT firms. [11] We find that non-HFT firms incur significantly higher adverse selection costs than HFT firms, while the opportunity costs of the limit orders for HFT firms are significantly higher than the limit orders of non-HFT firms, confirming that both are acting strategically for their respective purposes of trading.

We also compare the opportunity costs of limit orders cancelled by both groups. We find that the limit orders cancelled by HFT firms have significantly lower opportunity costs. Since

[9] The exogenous factors, including liquidity demand, financing costs, hedging demand, and other personal uses of the asset (e.g., arbitrages), are considered as ex post gains from trade in theoretical trading models (Duffie et al. 2010; Pagnotta and Philippon 2012).

[10] Economides and Schwartz (1995) provide further empirical evidence supporting this analysis. They survey 150 professional investors with $1.54 trillion in equity under management, and find that the majority of these investors rank non-execution risk ahead of adverse selection risk as the most important drawback of using limit orders (Economides and Schwartz 1995, Table 11).

[11] As explained in Section 1, the opportunity costs are defined as the subsequent price movements following a limit order submission, which are different from the price pressure examined by Hendershott and Menkveld (2014). In Hendershott and Menkveld (2014) the price pressure is defined as the deviations from the efficient price that a market intermediary pays to mean-revert her inventory. The adverse selection costs of limit orders are calculated as the signed returns of the bid-ask midpoint in a 30-second (short-term) and 300-second (longer term) period after order submission.

our measure of opportunity costs is based on the immediate price movements after order submissions, the opportunity costs can be interpreted as the information content of the limit orders (i.e., positive (negative) opportunity costs means market prices tend to move in the same (opposite) direction as the limit orders, should the order be executed). Therefore, our results indicate that HFT firms are more capable of identifying and cancelling their limit orders that later become cheap liquidity. Our difference-in-differences tests (comparing opportunity cost differentials for cancelled and submitted orders across HFT and non-HFT firms) confirm that liquidity provided by HFT firms has greater information content.

In our sample, about 30% of the limit orders submitted to the top 50 price levels of the LOB emanate from the 26 HFT firms. When markets become increasingly reliant on voluntary high-frequency liquidity providers, the increased liquidity may come at the cost of market stability. Hasbrouck (2015) demonstrates how quote volatility affects traders with heterogeneous trading speeds, while Kirilenko et al. (2014) and the CFTC/SEC's 2010 Report on the May 6, 2010 flash crash reveal how high-frequency liquidity providers may exit the market and cause further disruptions during extreme market conditions. Unlike designated market makers, voluntary liquidity providers may withdraw during volatile periods but, on the other hand, liquidity is also more expensive when markets are more volatile, which represents a profit opportunity for liquidity suppliers if they can manage the risk.[12] With superior trading technologies, HFT liquidity providers are better positioned to manage this risk and earn the additional risk-adjusted profits. Consistent with this analysis, we find that HFTs net increase the

[12] Hendershott and Riordan (2013) provide some evidence suggesting that algorithmic traders tend to consume liquidity when bid-ask spreads are narrow and supply when they are wide. Our study is different from Hendershott and Riordan (2013) who focus on algorithmic trading that includes both agency and proprietary trading, whereas our study considers the trading of firms identified as proprietary HFT traders. The purpose of trading for institutions with large positions can be vitally different from that of proprietary traders. Exclusively analyzing the behavior of the latter can shed important light on regulatory concerns.

supply of liquidity in large- and medium-cap stocks when market volatility increases, and provide more liquidity in large cap stocks during periods of extreme market volatilities. We also find that following shocks in market liquidity imbalances, both HFT and non-HFT liquidity providers place their limit orders further away from the top of the LOB, which is consistent with the behavior of rational voluntary liquidity providers. However, the impact of liquidity imbalance shocks on HFT liquidity providers is significantly smaller and diminishes more quickly than that on non-HFT liquidity providers. Our results thus suggest that although HFT liquidity is more informed, and thus, more expensive, overall, as liquidity providers, HFT firms enhance market quality.

Our study has important implications for the regulation of HFT. Recently there has been a wide-spread call for tightened regulations on HFT.[13] Our evidence should help market regulators to better understand the role played by HFT firms as liquidity suppliers during normal trading conditions, as well as the economics underlying the differences in the limit order placement behavior between HFT firms and non-HFT firms. Our results also bring into question the effectiveness of regulations that target some features such as fleeting orders commonly believed to be associated with HFT liquidity, which as we show are shared by non-HFT liquidity under the current trading environment.

The rest of paper is organized as follows. In Section 1, we describe the sample data. Section 2 provides the empirical results and analysis. We conclude and provide the policy

[13] In the United States, there are a large number of market regulators and law enforcement agencies currently investigating HFT activities, including the Federal Bureau of Investigation (FBI), Department of Justice (DOJ), the Securities and Exchange Commission (SEC), Commodity Futures Trading Commission (CFTC), the Office of the New York Attorney General, and the Massachusetts Secretary of Commerce (see, Shorter and Miller 2014). Legal actions were also launched against exchanges for their alleged granting of unfair advantages to HFTs. See "High-Frequency Trading Leads to Lawsuit Against Exchanges," *The Wall Street Journal*, September 8, 2014. In Europe, the Prudential Regulation Authority in the United Kingdom recently started testing "whether companies' controls around algorithmic, or automated, trading are fit for purpose" (see "High-frequency trading faces tougher Bank of England scrutiny," *Financial Times*, May 15, 2015).

implications of our study in Section 3.

1. Data

Nasdaq provides the full order and transaction data for 120 stocks traded on the Nasdaq markets over the first quarter of 2011. The 120 stocks are stratified by market capitalization and listing venues, as examined by Brogaard, Hendershott, and Riordan (2014). Three stocks were delisted before the sample period (BARE, CHTT, and KTII), and another stock is delisted (BW) during the sample period. Therefore, we delete these four stocks, giving a final sample of 116 stocks; 59 are listed on the NYSE and 57 are Nasdaq listed. We further sort the sample stocks by market capitalization and divide them into large (top 40 stocks), medium (medium 40 stocks), and small (final 36 stocks) size groups. Appendix 1 contains the list of stocks and their market capitalizations. Over the sample period, there are 26 HFT firms identified individually by Nasdaq based on their trading behavior and customers. We classify traders into HFT firms and non-HFT firms based on whether they are included in the Nasdaq HFT firm list.[14]

The order and transaction data are time stamped to the nanosecond with buy/sell indicators and trader IDs. Using these data we reconstruct the LOBs of each of the sample stocks over the sample period, and generate five datasets: the LOB snapshots dataset, the limit order traffic dataset, the limit order size dataset, the limit order survival time dataset, and the limit order opportunity costs dataset; these datasets are described below.

Each trading day is divided into five-second intervals. A snapshot of the LOB is taken at the end of each time interval; the LOB snapshots dataset contains the aggregated limit order volume placed by HFT firms and non-HFT firms at each of the top 50 price levels of the LOB at

[14] Brogaard, Hendershott, and Riodan (2014) provide additional explanation on the sample stock selection and the classification of HFT firms by Nasdaq.

the end of each time interval. The limit order traffic dataset contains the total buy and total sell limit order volume submitted and cancelled by each group during each time interval.

For each stock and trading day, the average and distribution quartiles of the size of limit orders submitted and cancelled by each group at the top 3, 4-10, 11-20, and 21-50 price levels of the LOB are calculated and output to the limit order size dataset. Similarly, for each stock and trading day, the volume-weighted average and distribution quartiles of the time it takes before a limit order is terminated, either by cancellation or by trade, are calculated for the top 3, 4-10, 11-20, and 21-50 price levels of the LOB, and output to the limit order survival time dataset.

Limit orders face opportunity costs if they are not executed and price subsequently moves away from them. Previous literature focuses on the execution costs of trades (e.g., Bessembinder and Kaufman, 1997a, b; Chan and Lakonishok, 1997; Keim and Madhavan, 1997). Harris and Hasbrouck (1996) examine the execution costs for limit orders. They define the ex post execution costs as the difference between the execution price and the same-side quote price five minutes later. Griffiths et al. (2000) calculate the opportunity costs as the change in the midquotes from immediately before the limit order arrives at the LOB to the time it is cancelled, plus additional execution costs assuming the order is then resubmitted as a market order. However, it is assumed in this method that the trader is pre-committed to the execution of the order and has to trade as soon as the limit order fails to execute. In the current HFT environment, professional traders frequently submit, cancel, and modify their limit orders based on a variety of trading strategies; hence, they are unlikely to have pre-commitment on the quantity and time that they have to trade with.

Keeping in mind the above observations, we follow Perold (1988) and Hendershott, Jones, and Menkveld (2011) and define the opportunity costs of a limit order as:

$$Opportunity\_costs_t = q_t \frac{(m_{t+n} - m_t)}{m_t}, \quad (1)$$

where m_{t+n} is the NBBO midpoint n seconds after the order submission or cancellation, and q_t is a buy sell indicator that equals to 1 (-1) if it is a buy (sell) limit order. For each stock day, limit orders are sorted by order size and a limit order submitted or cancelled is classified as a small, medium or large order if the order size falls into the top 5% (large-size group), between 50% and 95% (medium-size group), and the bottom 50% (small-size group) in the size distribution, respectively. For limit orders at the top three price levels of the LOB, the average and distribution quartiles of opportunity costs over a 30-second (short-term) and 180-second (long-term) time periods are calculated for HFT and non-HFT limit orders of different order size categories, and output to the limit order opportunity costs dataset.[15]

2. Results and Analysis

2.1 The characteristics of HFT firms' limit orders

2.1.1 Volume

Table 1 reports some descriptive statistics of the limit orders submitted and cancelled by HFT and non-HFT firms across all sample stocks.[16] Each trading day is divided into five-minute intervals, and the table reports the average volume submitted and cancelled by each group at the top 50 price levels of the LOB during the time interval. Panel A shows that HFT firms (non-HFT firms) on average submit 85,845 (202,463) shares of limit orders to the top 50 price levels of the LOB per five-minute interval per stock respectively, which indicates that over the sample period the 26 HFT firms contribute about 30% of the total liquidity on the LOB. Among the total limit

[15] We choose 30 seconds as the short-term time interval because as reported in Table 3 the average survival time of limit orders before cancellation is between 30 and 45 seconds.

[16] In Appendix 2, we divide our sample stocks into small, medium, and large groups based on their market capitalizations, and the statistics reported in Table 1 are reproduced for each stock group.

orders submitted by HFT firms (non-HFT firms), 67,092 shares (125,225 shares) or 78% (62%) are submitted to the top three price levels of LOB. This result indicates that relative to non-HFT firms, HFT firms are more likely to supply liquidity to the top of the LOB.[17]

[Insert Table 1 Here]

Table 1, Panel B shows that the average limit order volumes cancelled by both groups follow closely the volumes they submit (i.e., the total volume cancelled by non-HFT firms is greater than that by HFT firms, which tend to cancel more closer to the top of the LOB). An interesting question, therefore, is which type of trader is more likely to cancel a limit order? For each time interval, we calculate the cancellation ratio as the total limit order volume cancelled divided by the sum of limit order volume cancelled and submitted. Panel C shows that the limit order cancellation ratios of both groups are very high. For limit orders in the top three price levels of LOB, the average cancellation ratio for HFT firms is 0.4862, which is almost identical to the cancellation ratio of 0.4858 for non-HFT firms. The average cancellation ratio for all limit orders in the top 50 price levels is about 0.49 for both groups. Panel D reports the average order execution ratio, which is calculated as the total limit order volume executed divided by the total limit order volume submitted. The execution ratio is higher for non-HFT firms for orders in the top three price levels of the LOB; however, when we include all orders at the top 50 price levels, the difference between groups is economically small.

The results on cancellation ratio are contradictory to the common belief that relative to non-HFT firms, HFT firms are more likely to cancel their orders. For example, in the SEC Concept Release 2010 firms engaging in HFT are characterized by "… (4) the submission of

[17] During our sample period Nasdaq charges an excess message fee for limit orders that are more than 0.2% outside of the NBBO, a band that is equivalent to $0.09 based on the average price of $45 for our sample stocks. The significant decrease in limit orders outside the top 10 price levels is consistent with the notion that traders are sensitive to the increased costs for liquidity provision.

numerous orders that are cancelled shortly after submission" (SEC Concept Release 2010, p. 45). More recently, the SEC is reported to be considering options to curb HFT, including "charging fees for the myriad buy and sell orders that are later cancelled."[18] Our results suggest that limit orders from non-HFT firms are equally likely to be cancelled, and question the effectiveness of charging order cancellation fees as a measure to restrict HFT activities.

To further investigate order cancellation by HFT and non-HFT firms, Figure 1 shows the intraday order cancellation ratios for the small-, medium-, and large-cap stocks. It is apparent that the order cancellation ratios of both groups closely follow each other throughout the trading day. The cancellation ratios range between the levels of 0.48 and 0.5 for all stock groups, and are generally higher for smaller stocks, which is consistent with the higher risk in the trading of these stocks. An interesting result is the behavior of the cancellation ratio at the end of trading day. The cancellation ratios of both groups decrease towards the end of trading day; this decrease is more profound for non-HFT firms and for smaller stocks. Since order cancellation at high frequencies can serve as an effective tool to turn the nature of limit orders from supplying liquidity to demanding liquidity (Hasbrouck and Saar, 2009), a decrease in limit order cancellation rate may indicate an increase in a trader's intension to supply liquidity. To confirm this hypothesis, in Appendix 3 we calculate the intraday net liquidity supply for both groups, and find that there is a significant increase in net liquidity provision by both at the end of trading day. The pattern is consistent with the liquidity cancellation ratio presented in Figure 1. Brogaard (2010) finds that since HFT firms typically maintain a zero end-of-day inventory, these informed traders (Brogaard, Hendershott and Riordan 2014) initiate fewer trades when it gets closer to the end of trading. Therefore, we believe that the significant increase in liquidity supply especially

[18] See, "SEC May Ticket Speeding Traders," *The Wall Street Journal*, February 23, 2012. In addition, exchanges also consider order cancellation fee as an effective tool against HFT. For example, the Chicago Stock Exchange has been trying to design an optimal order cancellation fee scheme to restrict HFT. See, SEC File No. SR-CHX-2012-15.

for non-HFT firms at the end of trading is a strategic response to the reduced risk of trading against informed liquidity-taking HFT firms.

Large (2004) suggests that limit order cancellation is affected by the arrival rate of market orders. To investigate this assumption we calculate and plot the intraday volatilities using trade returns. Figure 1 shows that across all stock groups, volatility is elevated at the beginning of trading day, which decreases significantly in the next 15 minutes and then gradually decreases for the rest of the trading day. However, the cancellation ratio and intraday volatility do not share similar patterns.

[Insert Figure 1 Here]

2.1.2 Size

Table 2 reports the sizes of limit orders submitted and cancelled by HFT and non-HFT firms. As the table shows, the average sizes of limit orders submitted and cancelled are very small. The median size of a limit order submitted or cancelled is about 100 – 130 shares, depending on the market capitalization of the stock. In the majority cases, the cut-off level for the smallest 25% of orders (Q1) is below or equal to 100 shares. O'Hara, Yao, and Ye (2011) find that on average 19% of transactions executed on Nasdaq are odd lots. They attribute this observation to the slicing and dicing strategies of HFT firms when they take liquidity. We provide another explanation, which is that the odd lot trades can be the result of odd lot limit orders resting on the LOB from both HFT firms and non-HFT firms.

We next examine whether there are differences between the sizes of HFT and non-HFT limit orders. Depending on the market capitalization of the stock, the mean (median) size of limit orders submitted by HFT firms ranges between 118 shares (100 shares) and 196 shares (130 shares), while for non-HFT limit orders, the mean (median) size is between 230 shares (103

shares) and 388 shares (136 shares), respectively. Tests reported in Table 2 show that the size of limit orders submitted by HFT firms is significantly smaller than that of non-HFT firms for large- and medium-cap stocks. For small-cap stocks, the average size of limit orders is smaller for HFT firms but the median size is larger. This result indicates that for small-cap stocks there is a significant skewness in the underlying distributions of HFT and non-HFT limit order sizes. It is apparent that across all stock groups, the differences in median sizes between HFT and non-HFT limit orders are economically small.

[Insert Table 2 Here]

In Table 2, for all stock groups, the size of limit orders submitted by HFT firms to the top three price levels of the LOB is smaller than those submitted to the rest of price levels, while the opposite holds for non-HFT firms except for the small-cap stock group. Orders placed closer to the top of the LOB bear higher adverse selection risk, while those placed further away can benefit from transitory price volatilities (Ahn, Bae, and Chan 2001). Therefore, our results indicate that compared with non-HFT firms, HFT firms are more strategic in placing their limit orders. Table 2 also shows that the limit order size is the largest for large-cap stocks for both groups. The results for limit orders cancelled are very similar to those for limit orders submitted.

2.1.3 Survival time

Table 3 reports the volume-weighted average and distribution quartiles of the survival time of limit orders placed at different price levels of the LOB. Similar to Table 2, Panels A-C report the statistics for large-, medium-, and small-cap stock groups, respectively. The survival time of a limit order is calculated as the difference between the time when the order arrives at the LOB and the time the order is terminated either by cancellation or by execution.

[Insert Table 3 Here]

The most apparent result in Table 3 is that the survival time of limit orders at the top of the LOB is very short. For large- and medium-cap stocks, the median survival time of an HFT (non-HFT) limit order placed at the top three price levels is 1.53 (3.02) and 5.20 (5.70) seconds, respectively; for small-cap stocks, most limit orders sit at the top three levels for less than 20 seconds.

For large-cap stocks, the average time for an HFT limit order before being cancelled or executed is 28.74 seconds, if the order is placed at the top three price levels of the LOB. The survival time increases significantly to 96.12 seconds for an HFT order located between the price levels of 4 and 10, and to over 600 (900) seconds if it is located between levels 11 and 20 (21 and 50), respectively. The sharp increase in survival time for orders placed further from the bid-ask spread holds for both HFT and non-HFT orders across all stock groups. The shorter survival time of limit orders closer to the top of the LOB is consistent with the higher adverse selection risk at these price levels.

Table 3 shows that the average (median) time to cancellation for an HFT limit order placed at the top three price levels of the LOB is 28.25 seconds (0.53 second), 30.32 seconds (2.15 seconds), and 46.16 seconds (6.84 seconds) for large-, medium-, and small-cap stocks, respectively. Results of time to cancellation for non-HFT limit orders also show that limit orders placed close to the top of LOB are short-lived, and are cancelled more quickly for larger stocks. More importantly, for large- and medium-cap stocks, the time to cancellation at the top three price levels of the LOB is significantly shorter for HFT limit orders than non-HFT limit orders. For small-cap stocks, the average time to cancellation is longer for HFT limit orders, while the median time to cancellation is indifferent between HFT and non-HFT limit orders. These results

indicate that both groups actively monitor and manage their limit orders placed at the top of the LOB, and HFT limit orders are cancelled more quickly than non-HFT limit orders for the large- and medium-cap stocks. Table 3 also reports the average and median time to execution for HFT and non-HFT limit orders. Across all stock groups the time to execution is significantly shorter for HFT limit orders, which indicates that HFTs are more capable of predicting incoming market orders. In general, the results in Table 3 confirm the general perception that the liquidity provided by HFT firms stays on the LOB for a shorter period of time.

2.1.4 Distribution along LOB

Table 4 reports the results of an examination of how HFT liquidity is distributed across the LOB. We take a snapshot of the LOB at the end of each five-second interval of a trading day, and calculate the percentage of limit order volume submitted by HFT firms for each of the top 50 buy and sell price levels of the LOB. Panels A-C report the results for large-, medium-, and small-cap stock groups, respectively. To control for the ex ante market risk faced by liquidity providers, for each stock and each five-second time interval, we calculate the absolute values of the bid-ask midpoint log returns. We classify a time interval as a high, medium or low risk interval if the absolute return of the interval falls into the top 1%, between 90% and 99%, and below 90% levels of the distribution, respectively. The average percentage of HFT limit order volume is then calculated for each class of time intervals.

[Insert Table 4 Here]

The results in Table 4 show that on average the 26 HFT firms in our sample contribute about 42%, 33%, and 23% of the total liquidity at the best bid and offer for large-, medium-, and small-cap stocks, respectively. The percentage of HFT liquidity decreases at an increasing speed

as price moves away from the BBO. These results are consistent with those reported in Table 1.

The liquidity provided by HFT firms is more concentrated in stocks of larger market capitalization, which is consistent with Menkveld (2013), who reports that the high-frequency market maker examined in his study participates in more trades in large stocks. For large- and medium-cap stocks, the percentage of liquidity provided by HFT firms is positively related to price risk. Specifically, relative to non-HFT firms, HFT firms provide more liquidity during high risk periods. We also calculate the cumulative proportion of HFT volume (not reported). We find that as the risk level increases from low to medium or from medium to high, the percentage of HFT liquidity at the top three price levels of the LOB increases by about 16% for large-cap stocks and 9% for medium-cap stocks, respectively. The results that HFT firms increase their liquidity provision during market volatility are consistent with the conjecture that they are better at managing risk and are more capable of providing liquidity when it is needed. This finding is consistent with Carrion (2013), who shows that HFT firms provide more liquidity in transactions when bid-ask spreads are wider. For small-cap stocks, the percentage of HFT volume is more evenly distributed across different risk levels, which confirms that voluntary market makers are more challenged in providing liquidity for small stocks (Grossman and Miller 1988; Bessembinder, Hao, and Zheng 2014).[19]

2.2 Are HFT limit orders informed?

2.2.1 The LOB slope

If HFT and non-HFT firms are different in their information endowments, it should be reflected

[19] Another interesting result of Table 4 is that, for medium- and small-cap stocks and for large cap stocks during high risk periods, the percentage of HFT liquidity is not the highest at the BBO price levels but rather at 1 tick from the BBO. This may indicate that HFT firms strategically place limit orders to avoid adverse selection risk and benefit from transitory volatilities when markets are more volatile.

in how they place limit orders. Naes and Skjeltorp (2006) find that the slope of the LOB is strongly related to future return volatility. In this section, we examine the LOB slopes based on HFT and non-HFT limit orders to determine the relation between future price volatility and how the firms place their liquidity on the LOB.

First, we visually compare the shapes of the LOBs constructed separately from HFT and non-HFT limit orders. More specifically, a snapshot of the LOB is taken at 9:30:30, 10:00:00, 12:00:00, 15:00:00, and 15:59:30, and the limit orders placed by HFT s and non-HFT firms are identified for each of the top 50 price levels. The HFT (non-HFT) LOB shape shown in Figure 2 is the average cumulative volume of HFT (non-HFT) limit orders divided by the average cumulative total depth at each price level of the LOB.

[Insert Figure 2 Here]

The HFT LOB shape in Figure 2 exhibits a clear intraday pattern for all stock groups; it is relatively flat around the BBO at the start of the trading day, and becomes steeper as it moves towards the close. The change in shape is generally monotonic in time and coincides with the intraday volatility pattern shown in Figure 1. On the other hand, the intraday pattern of the non-HFT LOB shape is unclear for all stock groups. Placing limit orders further from the top of the LOB during high market volatility is consistent with strategic trading behavior. Indeed, Ahn, Bae, and Chan (2001) find that traders benefit from trading with limit orders if the transitory volatility is high. In addition, the inventory risk of liquidity providers also prevents them from taking aggressive positions during high volatility periods. Thus, Figure 2 indicates that compared with non-HFT firms, HFT firms are more strategic in placing limit orders.

Next, we formally test the relative informativeness of HFT and non-HFT firms when they place limit orders on the LOB, following the methodology proposed by Naes and Skjeltorp

(2006). More specifically, the LOB slope is calculated as:

$$Slope_t = \frac{1}{N}\left(\frac{v_1}{\left|\frac{p_1}{p_0}-1\right|} + \sum_{n=1}^{N}\frac{v_{n+1}-v_n}{\left|\frac{p_{n+1}}{p_n}-1\right|}\right), \quad (2)$$

where p_n and v_n are the price and volume at the *n*-th price level of the LOB, respectively,[20] and p_0 is the bid-ask midpoint. Since the sensitivity to market risk may be different for limit orders placed at different price levels, we calculate the order book slopes based on HFT and non-HFT limit orders placed at the top 3, 4-10, 11-20, and 21-50 price levels of the LOB separately. Each trading day is divided into five-second intervals, and the HFT and non-HFT LOB slopes are calculated at the end of each interval.

To examine the information content in the HFT and non-HFT LOB slopes, we follow Jones, Kaul, and Lipson (1994) and Naes and Skjeltorp (2006) and estimate the following regressions:

$$R_t = \sum_{n=1}^{12} R_{t-n} + \sum_{m=2}^{26} D_m + \varepsilon_t. \quad (3)$$

$$|\varepsilon_t| = \sum_{n=1}^{12}|\varepsilon_{t-n}| + \sum_{m=2}^{26} D_m + \sum_{j=2}^{116} D_j + Turnover_T + MktCap_T + \frac{1}{P_T}$$
$$+Size_t + Trades_t + Slope_{t-1} + Depth_{t-1} + \eta_t. \quad (4)$$

R_t is the bid-ask midpoint return for interval t and D_j are stock dummy variables. Each trading day is further divided into 26 15-minute intervals, and D_m are dummy variables for these time intervals. $Turnover_T$, $MktCap_{T,}$ and P_T are the share turnover, market capitalization, and average trade price for the current stock on day T, and $Size_t$ and $Trades_t$ are the average trade size and the number of trades at interval t, respectively. $Depth_t$ is the total limit order volume available at the corresponding price levels. Under this model specification, the intraday volatility is estimated in Eq. (3) for each stock as the absolute value of the return residuals after controlling

[20] The limit order volume is standardized by the total shares on issue of the current stock.

for the persistence in returns. In Eq. (4), the relation between the LOB slope and future price volatility is estimated after controlling for variables known to have an impact on volatility. The results are reported in Table 5.

[Insert Table 5 Here]

Table 5 shows that the LOB slope constructed by using HFT limit orders is consistent with future price volatility. The coefficients of HFT LOB slope are negative and significant (except for the slope at the 21-50 price levels in large- and small-cap stocks), suggesting that HFT firms remove limit orders located closer to the front of the LOB and place more at the back of the LOB ahead of an immediate increase in price volatility. For non-HFT LOB slope, the coefficient is positive for the top three price levels for large-cap stocks, which suggests that non-HFT firms place more limit orders closer to the top of the LOB before an increase in volatility. Although the rest of the coefficients of non-HFT slope are mostly negative and significant, statistical tests reported in Table 5 show that the sensitivity of the HFT LOB slope to future price volatility is significantly higher than that of non-HFT LOB slope for all categories in the top 20 price levels.

Brogaard, Hendershott, and Riordan (2014) show that HFT firms are more informed when initiating trades. Our results complement their findings and indicate that the informational advantage of HFT firms extends to their limit order placement. In particular, our results in Table 5 show that HFT firms can predict short-term price volatility more accurately and better adjust their exposure on the LOB ahead of the risk than non-HFT firms.[21]

Table 5 also shows that the greater the depth on the LOB, the lower the future price volatility, and this relation is more sensitive for orders at the top three price levels. The negative

[21] An alternative explanation for our findings is that HFTs strategically place their limit orders on the LOB, which triggers future price volatility. However, this cannot explain the results presented in the next section, where we find an asymmetric impact on returns between limit orders added and canceled by HFT and non-HFTs firms.

relation between LOB depth and price volatility supports the prediction by Foucault, Roell, and Sandas (2003) in that informed liquidity providers bid less aggressively if they believe that future volatility will be high. We also find that volatility is positively related to trading turnover and market capitalization. For large- and medium-cap stocks, volatility is positively related to trade size and the number of trades, and negatively related to average price, while the opposite holds for small-cap stocks.

2.2.2 Limit order placement activities and future returns

Brogaard, Hendershott, and Riordan (2014) suggest that HFT firms initiate transactions in the direction of future price movements. If the technological advantages enable HFT firms to do so when they take liquidity, it is possible that their liquidity provision activities are also informed. We test this hypothesis by estimating the following regression:

$$R_t = \sum_{i=1}^{12} R_{t-i} + \sum_{m=2}^{26} D_m + \sum_{j=2}^{40} D_j + Turnover_T + MktCap_T + \frac{1}{P_T} + Size_t^{Buy} + Size_t^{Sell} + Trades_t^{Buy}$$
$$+ Trades_t^{Sell} + Order\_added_{t-1}^{HFT\_buy} + Order\_added_{t-1}^{HFT\_sell} + Order\_added_{t-1}^{Non-HFT\_buy}$$
$$+ Order\_added_{t-1}^{Non-HFT\_sell} + Order\_cancelled_{t-1}^{HFT\_buy} + Order\_cancelled_{t-1}^{HFT\_sell}$$
$$+ Order\_cancelled_{t-1}^{Non-HFT\_buy} + Order\_cancelled_{t-1}^{Non-HFT\_sell} + \varepsilon_t. \quad (5)$$

Each trading day is divided into five-second intervals. $Size_t^{Buy}$ ($Size_t^{Sell}$) and $Trades_t^{Buy}$ ($Trades_t^{Sell}$) are the average size of buyer- (seller-) initiated trades and the number of buyer- (seller-) initiated trades during interval t, respectively. $Order\_added_t^{HFT\_buy}$ ($Order\_added_t^{HFT\_sell}$) and $Order\_added_t^{Non-HFT\_buy}$ ($Order\_added_t^{Non-HFT\_sell}$) are the total buy (sell) limit order volume submitted by HFT and non-HFT firms during interval t, respectively. Similarly, $Order\_cancelled_t^{HFT\_buy}$ ($Order\_cancelled_t^{HFT\_sell}$) and

$Order\_cancelled_t^{Non-HFT\_buy}$ ($Order\_cancelled_t^{Non-HFT\_sell}$) are the total buy (sell) limit order volume cancelled by HFT and non-HFT firms during interval t, respectively. The rest of variables are as defined in Eq. (4). Table 4 shows that the proportion of HFT liquidity drops quickly beyond the top three price levels of the LOB, therefore we only include limit orders submitted and cancelled within the top three price levels when calculating the order addition and cancellation metrics. Except for the dummy and return variables, all variables are log transformed. The results are reported in Table 6.

[Insert Table 6 Here]

Table 6 shows that an increase in buy (sell) limit orders for both groups is associated with an increase (decrease) in future returns. For example, for large-cap stocks, a 10% increase in the HFT (non-HFT) buy limit order volume in the previous five-second interval leads to an increase of 0.00064 (0.00097) bps in the returns of the following five-second interval, while a 10% increase in the HFT (non-HFT) sell liquidity in the previous five-second interval lowers the returns in the following five-second interval by 0.00065 (0.00092) bps, respectively. The impact of limit orders on returns is greater for non-HFT firms, which is not surprising given that their average limit order volume is almost double that of HFT firms (Table 1, Panel A).

More importantly, the limit orders cancelled by HFT firms are consistent with future price movements, while this relation is less significant for those cancelled by non-HFT firms. A 10% increase in the buy (sell) limit orders cancelled by HFT firms is associated with a decrease (increase) of 0.00014 (0.0002), 0.00043 (0.00046), and 0.00014 (0.00015) bps in future returns for large-, medium-, and small-cap stocks, respectively. The relation between the order cancellation of non-HFT firms and future returns is the opposite for large-cap stocks; for medium- and small-cap stocks, it is significantly weaker than that of HFT firms. The results for

order cancellation are especially interesting since, similar to the limit order volume submitted, the limit orders cancelled by non-HFT firms at the top three price levels are also close to double those of HFT firms (Table 1, Panel B). Since limit orders submitted or cancelled are associated with future price movements, this result weakens the assertion that order cancellation by HFT firms causes future price volatility. It provides support for the alternative explanation that traders use order cancellation to actively manage the risk exposure of their limit orders and HFT firms are more capable of doing so than non-HFT firms.

The results for the control variables are mostly as expected. Larger buy (sell) limit orders and more buy (sell) trades are associated with a contemporaneous increase (decrease) in returns. We also find that market capitalization and the inverse of average price are negatively (positively) related to price returns for large-cap (medium- and small-cap) stocks, respectively.

2.3 The informational content of HFT firms' limit orders

The results in Section 2.2 consistently support that HFT firms are more informed when supplying liquidity on the LOB. Liquidity providers face two types of risk: the adverse selection risk if their liquidity is taken by informed traders and the opportunity costs if their orders are not executed and price subsequently moves away. Liquidity providers actively monitor and manage their exposure on the LOB to balance between these two types of risk (Liu 2009). In this section, we provide further analysis on the relative performance of HFT and non-HFT firms when they supply liquidity and assess how they manage these risks.

First, we compare the adverse selection costs of liquidity provided by HFT and non-HFT firms in transactions. Following Hendershott, Jones, and Menkveld (2011), the adverse selection costs of limit orders executed in transactions are calculated as:

$$Adverse\ selection\ cost_t = q_t \frac{(m_{t+n} - m_t)}{m_t}, \quad (6)$$

where m_t and m_{t+n} are the NBBO midpoint at time t and n seconds, respectively, after time t, and q_t is a buy (sell) indicator, which equals to -1 (1) if it is a buy (sell) trade.[22] For each stock, transactions are sorted by trade size over the sample period, and those falling into the top 5%, between 50% and 95%, and the bottom 50% of the trade size distribution are classified as small, medium, and large trades, respectively. For each stock day and trade size category, we calculate the volume-weighted average adverse selection costs of limit orders submitted by HFT firms or non-HFT firms over a 30-second (short-term) and 180-second (long-term) period.

The results in Table 7 show that the adverse selection costs for HFT limit orders executed in transactions are significantly lower than those of non-HFT firms for all trades in large-cap stocks, as well as for the medium- and small-size trades in medium-cap stocks. The average adverse selection costs of HFT liquidity executed in small-cap stocks are also lower than those of non-HFT firms, but the difference is generally insignificant. These results show that HFT firms are more capable of identifying informed liquidity takers, especially for larger stocks and in smaller trades. This informational advantage of HFT firms in supplying liquidity is more significant over a short-term period than a long-term period, as the differences in adverse selection costs between groups are generally greater over the short term.

[Insert Table 7 Here]

Table 7 also shows that all limit orders incur adverse selection costs, which indicates that liquidity takers on average are more informed than liquidity providers. This result is consistent with Harris and Hasbrouck (1996, p. 215), who find that "if a trader passively places limit orders, and then (upon execution) actively attempts to reverse the initial trade, losses are likely to

[22] Here we follow the conventional calculation of adverse selection costs in trades. If the limit order in a trade is a buy (sell) order, then the trade is seller- (buyer-) initiated.

result," and Benos and Sagade (2015), who find that aggressive HFT firms are the most informed among all types of HFT firms. Menkveld (2013) also shows that high-frequency market makers lose on their inventory positions to liquidity takers. We also find that the adverse selection costs of limit orders executed increases (decreases) monotonically with trade size (stock size). This finding indicates that adverse selection risk is higher for liquidity providers when they participate in larger transactions and less liquid stocks.

Our results in Table 7 show that non-HFT firms incur higher adverse selection costs than HFT firms when providing liquidity in transactions, especially for large- and medium-cap stocks. However, the differences in adverse selection costs can be the result of their rational behaviors. In particular, unlike HFT firms who are professional traders and hence more sensitive to short-term price movements, non-HFT firms may include investors with a trading interest based on their expected long-term stock performance (e.g., value investors) or temporary liquidity demand (e.g., a mutual fund manager receiving client requests). Hence, for non-HFT firms, the final success of an order being executed can be more important (Economides and Schwartz 1995). Hoffman (2014) demonstrates that to compete with those more informed, traders increase the aggressiveness of their quotes to maintain a constant execution probability. Therefore, the higher adverse selection costs incurred by non-HFT firms documented in Table 7 can be due to their strategic behavior of posting limit orders more aggressively in order to achieve a better execution rate.

Griffiths et al. (2000) find that the more aggressive the limit orders are the less opportunity costs they incur. Therefore, to test the hypothesis, for each stock group we calculate the volume-weighted average opportunity costs of all limit orders submitted and cancelled by HFT and non-HFT firms using the limit order opportunity costs dataset described in Section 1.

[Insert Table 8 Here]

The results in Panel A of Table 8 show that the opportunity costs of limit orders are all positive, and similar to the adverse selection costs reported in Table 7. The opportunity costs are positively related to stock liquidity and generally increase with order size (except for large orders in large-cap stocks). Hendershott, Jones, and Menkveld (2011) find that liquidity providers charge an effective spread to cover the costs associated with market making. Using national consolidated transaction data of the same sample stocks and sample period, Hatheway, Kwan, and Zheng (2013) find that the realized spreads, which are the differences between the effective spreads and the adverse selection costs, are close to zero on exchanges even after liquidity rebates. They conclude that trading on exchanges is highly toxic for liquidity providers. Our results indicate that liquidity providers are informed about short-term price movements and strategically charge a liquidity premium in addition to the effective spreads to assert a competitive stance against the informed liquidity takers.

The results in Table 8 on the partition of HFT firms and non-HFT firms follow a similar pattern as those reported in Table 7. For all orders in large-cap stocks and small orders in medium-cap stocks, limit orders placed by HFT firms incur significantly higher opportunity costs than those placed by non-HFT firms over both short- and long-term periods (except for large orders over the long-term period); in the rest categories, opportunity costs are generally higher for non-HFT limit orders.

Table 8 also reports the percentages of small, medium, and large limit orders submitted by HFTs and non-HFT firms. It is apparent that the majority of limit orders are in the small size category. Therefore, our results indicate that HFT firms are more capable of supplying liquidity in larger stocks and smaller transactions, where they charge a higher liquidity premium to offset

the adverse selection costs. These results also provide supportive evidence of our earlier findings that HFT firms are more aggressive in providing liquidity in larger stocks (Table 4).

The results in Panel B of Table 8 show that limit orders cancelled by HFT firms incur lower opportunity costs than those cancelled by non-HFT firms and the differences are statistically significant across all categories. These results suggest that compared with non-HFT firms, HFTs are more capable of identifying and canceling liquidity that later becomes cheap, which also suggests that they are more informed than non-HFT firms.

For small-cap stocks, the opportunity costs of HFT firms are lower for both the limit orders they submit and those they cancel. An interesting question, therefore, is whether there is any difference between the groups in the opportunity costs they incur for orders cancelled relative to orders submitted. We first determine (1) the differences in the opportunity costs of orders submitted by both groups, as well as (2) the differences in opportunity costs of orders cancelled by both groups. We then subtract (2) from (1) for each corresponding order and trader types.

Panel C of Table 8 shows that the results of the difference-in-differences tests are positive and significant for all orders for large-cap stocks and for small and median orders for medium-cap stocks. The results for small orders in small-cap stocks are also positive and significant. These results indicate that relative to non-HFT firms, HFT firms are more capable of identifying and cancelling liquidity with lower opportunity costs, and lends further support to our results in Tables 5 and 6 that HFT firms are more capable of using order cancellation to monitor and manage their limit order risk exposure. Since the majority of orders submitted and cancelled are in the small size category, our results are consistent with the conjecture that when supplying liquidity, HFT firms utilize their superior trading technology (i.e., the ability to cancel orders

quickly) and information about short-term price movements to charge a higher liquidity premium in an attempt to reduce the adverse selection imposed by better-informed liquidity takers. This higher liquidity premium explains the lower adverse selection costs for HFT limit order in transactions documented in Table 7. Our results also provide supportive evidence consistent with the projection that non-HFT firms incur higher adverse selection costs in transactions because they are more aggressive in placing limit orders. As discussed above, such behavior can be rational if non-HFT firms strategically expose their limit orders to higher adverse selection risk when their trading intension is not directly related to short-term stock performance.

Table 8 demonstrates that limit orders are informed. Ahn, Bae, and Chan (2001) suggest that limit orders can be optimal for traders with long-term information. However, the ex post price movements documented in Table 8 are measured over a relatively short time period. Why do traders place limit orders if they possess short-term information? To investigate this issue we compare the relative spreads immediately before a limit order is placed with the opportunity costs incurred for the limit order. For each stock day and order size category, we calculate the average relative spreads immediately before a limit order is placed at the NBBO price levels.[23] We then compare the relative spreads with the opportunities costs of the limit order.

Table 9 shows that for the HFT limit orders, the average relative spreads range from 3.5 bps (large-cap stocks) to 32 bps (small-cap stocks), while the long- and short-term opportunity costs are mostly 1-2 bps across all order sizes and stock groups. The relative spreads for limit orders are similar for both groups. Consistent with Table 8 results, the opportunity costs of non-

[23] We only use limit orders placed at the NBBO when comparing relative spreads and opportunity costs. First, traders placing limit orders at the NBBO are most keen to have their orders executed, and hence they are more likely to consider market orders as an alternative. Traders placing limit orders further from the NBBO may have other strategic considerations. Second, the exclusion of other limit orders in the calculation also creates a bias against us, because a trader who is only willing to place limit orders at the back of the LOB must pay more to turn them into market orders.

HFT firms are generally smaller than those of HFT firms for larger stocks and smaller orders. More importantly, our results confirm that across all categories, the relative spreads are significantly larger than the opportunity costs. These results show that a limit order is submitted when the trader's short-term information is not sufficient to cover the transaction costs of a market order. Our results are consistent with Bloomfield, O'Hara, and Saar (2005), who show that informed traders tend to submit limit orders when their information level is low. Table 9 also shows that the limit order opportunity costs increase with order size and decrease with stock size, consistent with Table 8. The relative spreads exhibit a similar pattern.

[Insert Table 9 Here]

2.4 The impact of HFT limit orders on market volatility

The SEC Concept Release 2010 (p. 48) raises a question on HFT: Is there any evidence that proprietary firms increase or reduce the amount of liquidity they provide to the market during times of stress? To answer this question, we use two proxies for market stress: price volatility and liquidity imbalance shocks. We are interested in how HFT firms supply liquidity following market volatility, as well as how they react to shocks in liquidity imbalances on the LOB.

We first examine the liquidity provision of HFT firms following market volatility. Table 1 shows that both HFT firms and non-HFT firms have a high order cancellation ratio. To measure the liquidity meaningful to liquidity demanders, we divide each trading day into 30-second intervals, and calculate for each interval the net HFT (non-HFT) liquidity as the difference between total limit order volume submitted and cancelled.

The relation between net liquidity provision and market volatility is modeled as:

$$Net\_liquidity_t = D_{HFT} + \sum_{m=2}^{26} D_m + \sum_{j=2}^{40} D_j + Turnover_T + MktCap_T + \frac{1}{P_T} + Size_t$$

$$+Volatility_{t-1} + D_{HFT} \times Volatility_{t-1} + D_{x\_vola} \times D_{HFT} \times Volatility_{t-1} + \varepsilon_t. \quad (7)$$

$Net\_liquidity_t$ is the net liquidity provided by HFT firms or non-HFT firms within five price levels of the LOB during interval t.[24] D_{HFT} is a dummy variable that equals 1 if the current net liquidity provision is for an HFT firm, or 0 otherwise. $Volatility_t$ is the standard deviation of second-by-second bid-ask midpoint returns during interval t. All other control variables are defined as in Table 5. To further identify periods of market stress, we sort $Volatility_t$ for each stock over the sample period, and use dummy variable D_{x_vola} to represent the largest 1% of volatility.[25] To reduce cross-sectional variation, we standardize all continuous variables by stock.

[Insert Table 10 Here]

Table 10 shows that the coefficient of $Volatility_t$ is negative for large-cap stocks and positive for small-cap stocks, which indicates that non-HFT firms on average reduce the net liquidity supply in large-cap stocks and increase liquidity supply in small-cap stocks following an increase in market volatility. There is no significant change in the liquidity provision by non-HFTs in medium-cap stocks. The coefficient of D_{x_vola} is positive and significant for large- and medium-cap stocks, which indicates that non-HFT firms provide more liquidity following an unusually high market volatility in these stocks. Since liquidity is more expensive during high volatility, liquidity suppliers can earn an additional liquidity premium.

In Table 10, the coefficient of D_{HFT} is negative and significant for large-cap stocks, which suggests that on average HFT firms provide less net liquidity than non-HFT firms. This is consistent with Table 1, which shows the total limit order volume for HFT firms is lower than that for non-HFT firms. More importantly, the coefficient of $D_{HFT} \times Volatility_t$ is positive and

[24] Other than the 30-second interval, we also use intervals of 5 seconds, 60 seconds, 180 second, 300 seconds, and 900 seconds. Our results are robust to these alternative time intervals.

[25] Brogaard, Hendershott, and Riordan (2014) use a 10% cut-off level to identify days of market stress. Since our sampling time interval is much shorter and may contain more noise, we adopt a tighter threshold. The 1% threshold is also widely used in the literature to identify jumps in intraday volatility (e.g., Lee and Mykland 2008).

significant for large- and medium-cap stocks. Specifically, relative to the net liquidity provided by non-HFT firms, a one standard deviation increase in price volatility leads to an additional 0.11 standard deviation increase in the net liquidity supply by HFT firms in the following period for large-cap stocks, and 0.02 standard deviation increase for medium-cap stocks. For small-cap stocks, the coefficient is negative and insignificant, which indicates that the liquidity supply by HFT firms is indifferent from that of non-HFTs following market volatility. The coefficient of $D_{x\_vola} \times D_{HFT}$ is positive and significant for the large-cap stocks, suggesting that HFTs provide more liquidity in these stocks following exceptionally high market volatility. In particular, a one standard deviation increase in extreme volatility is followed by an additional 0.06 standard deviation increase in the net liquidity provision by HFT firms. The coefficient of $D_{x\_vola} \times D_{HFT}$ is insignificant for medium- and small-cap stocks, suggesting that the liquidity supply by both groups is similar following extreme market volatility. These results indicate that for liquid stocks, HFT firms can manage the limit order risk more effectively and increase the net supply of liquidity following an increase in volatility. This finding is consistent with the prediction of Jovanovic and Menkveld (2011) that as the middleman between buyers and sellers, HFT firms increase their participation when there is more information on the market. Our results show that for less liquid stocks, both groups play a similar role in the supply of liquidity post market volatility.

We next examine how HFT and non-HFT firms react to liquidity imbalance shocks. Previous research demonstrates that abnormal order imbalances precede market vitality. For example, Chordia, Roll, and Subrahmanyam (2005) find that excessive buy or sell limit orders on the LOB can trigger large short-term price movements. Chordia, Roll, and Subrahmanyam (2008) demonstrate that this effect is more profound when market liquidity is low. To examine

the relation between market liquidity imbalance shocks and limit order placement by HFT and non-HFT firms, we estimate the following model:

$$Slope_t = \sum_{j=2}^{116} D_j + \sum_{m=1}^{10} Resi\_OI_{t-i} + D_{HFT} + \sum_{n=1}^{10} D_{HFT} \times Resi\_OI_{t-n} + \eta_t. \quad (8)$$

Consistent with Eq. (7), each trading day is divided into 30-second intervals. $Slope_t$ measures the slope of the LOB at the end of each interval, and is calculated following Eq. (2). We calculate the buy and sell LOB slopes separately. D_j are stock dummy variables. $Resi\_OI_t$ measures shocks in the liquidity imbalances and is obtained from the residuals of the regression:

$$OI_t = \sum_{m=1}^{10} OI_{t-i} + \eta_t. \quad (9)$$

For each time interval, we calculate the net buy (sell) limit order volume as the difference between the buy (sell) limit order volume submitted and cancelled. The net order imbalance OI_t is the difference between the net buy limit order volume and the net sell limit order volume. D_{HFT} is a dummy variable that equals 1 if the $Slope_t$ is constructed by using limit orders from HFT firms, and 0 otherwise. In Eq. (9), the net order imbalance is modeled as an autoregressive process, and the order imbalance residuals represent liquidity shocks on the current market. Therefore, we can use Eq. (8) to examine how HFT and non-HFT firms adjust their limit order placement in response to past liquidity shocks. We include orders placed in the top 10 price levels of the LOB when estimating Eq. (9). For Eq. (8), all variables are standardized by stock except for the dummy variable.

A distinct feature of our models is that we measure liquidity imbalance based on limit order volume instead of trading volume. Previous research tends to use trading volume imbalance as the proxy for order imbalance (e.g., Chordia, Roll and Subrahmanyam, 2002), which is essentially a proxy for the imbalance of market orders. O'Hara (2015, p. 19) argues that "algorithmic trading means that trades are not the basic unit of market information – the

underlying orders are." With liquidity imbalance calculated based on the net inflow of limit orders over a short time frame, we are able to capture the underlying price pressure, as well as the associated risk faced by limit order traders. Thus, our model is more predictive of how liquidity providers will react strategically to the dynamics on the LOB.

In Table 11, Panel A (Panel B) reports the estimates of Eq. (8), where the LOB slope variable is constructed by using buy (sell) limit orders, respectively. As the table shows, D_{HFT} is positive and significant in both Panels A and B, which is consistent with Table 4, and indicates that HFT firms tend to place more orders near the top of the LOB. The results also show that lagged liquidity shocks have a positive impact on the buy slope of non-HFT liquidity but have the opposite effect on its sell slope. Since liquidity imbalance is measured as the difference between net buy and sell limit order volumes, this result indicates that following a positive shock in the liquidity imbalance, non-HFT firms update their limit orders on the LOB in the same direction as the liquidity shock (i.e., placing more buy orders closer to, and moving more sell orders away from, the top of the LOB). Although the effect of the shocks reduces over time, the coefficient of $Resi\_OI_t$ remains significant after 10 lags. This placement strategy helps protect liquidity suppliers from being picked off by liquidity takers. However, such strategies can further exacerbate the prevailing order imbalance and market volatility.

[Insert Table 11 Here]

The coefficients of lagged $D_{HFT} \times Resi\_OI_t$ are negative and significant in Table 11, Panel A, which indicates that following a positive (negative) shock in order imbalance, HFT firms place less (more) buy orders closer to the best bid price *relative* to non-HFT firms. The magnitude of the coefficients also exhibits an interesting pattern. The coefficient of $D_{HFT} \times Resi\_OI_{t-1}$ is smaller than that of $Resi\_OI_{t-1}$, showing that immediately after the liquidity

shock, both HFT and non-HFT firms adjust their limit orders in the same direction of the shock. Over time, the lagged coefficients of $D_{HFT} \times Resi\_OI_t$ increase in value and their magnitudes become closer to those of the coefficients of *lagged* $Resi\_OI_t$, which indicates that the impact of the liquidity shocks on the limit order placement of HFT firms quickly fades away. This is in direct contrast to the impact of liquidity shocks on non-HFT firms, which generally decreases but remains significant after 10 lags. The results in Panel B are consistent with those in Panel A. These results indicate that HFT firms are less affected and recover more quickly following liquidity shocks than non-HFT firms. Therefore, our results indicate that HFT liquidity providers reduce the impact of liquidity imbalance shocks. This finding is consistent with our previous results that HFT firms are better informed and can more effectively manage risk when supplying liquidity to the market.

3. Conclusions and Policy Implications

With the recent proliferation of HFT around the world, HFT firms have largely taken the role of traditional market makers (Jones 2013). Using a unique dataset, we conduct a close examination of liquidity provision by a group of HFT firms for 116 stocks traded on the Nasdaq during normal trading conditions.

First, our results clarify some commonly believed features associated with HFT liquidity. The SEC Concept Release 2010 (p. 67) identifies five major characteristics attributed to HFT firms that include the "submission of numerous orders that are cancelled shortly after submission." Our results show that the limit order cancellation ratio is almost identical between HFT firms and non-HFT firms. The sizes of limit orders are also similar between the two groups. The average time a limit order rests on the LOB is shorter for the limit orders of HFT firms, but

the absolute time to execution and time to cancellation are also very short for non-HFT limit orders and in many cases they are not much longer than those of HFT firms. Overall, our results confirm the recent comments of O'Hara (2015, p. 9) that "all trading is now fast, with technological improvements originally attaching to HFTs permeating throughout the market place," and question the effectiveness of some regulatory proposals targeting HFT.[26]

Second, in the context of the CFTC/SEC report based on the May 6, 2010 flash crash, we provide new evidence on HFT liquidity provision during *normal* market conditions, which is important for an understanding of the overall role played by HFT firms. The CFTC/SEC report concludes that "it appears that the 17 HFT firms traded with the price trend on May 6 and, on both an absolute and net basis, removed significant buy liquidity from the pubic quoting markets during the downturn." However, Jones (2013) argues that it is unrealistic to ask any market makers to provide liquidity during such extreme and rare market volatility. This brings into focus the role played by voluntary market makers during normal trading conditions. Our results indicate that the technology that HFT liquidity providers employ helps them to effectively manage risk under normal trading conditions, which in turn enhances market quality.

Third, our results bring into question the rationale behind the calling for tightened regulations on HFT because the liquidity provided by HFT firms is harder to access. We show that these firms are more capable of using order cancellation to manage adverse selection risk, which results in their limit orders being more informed. We also demonstrate that the order placement activities of non-HFT firms are consistent with their reason for trading not being directly related to the short-term performance of prices.

[26] For example, under MiFID II, "trading venues will be required to set limits on the maximum number of order messages that a market participant can send relative to the number of transactions they undertake." Financial Conduct Authority, 12/09/2014. URL: https://www.fca.org.uk/firms/markets/international-markets/mifid-ii/what-is-changing. Accessed on May 25, 2015.

Finally, our results reveal further perspective on the regulation of HFTs. Our results show that when providing liquidity, HFT firms net increase the supply of liquidity when market volatility increases and their liquidity is less affected by swings in order imbalances. Malinova, Park, and Riordan (2013) and Friederich and Payne (2015) examine the impact of new market regulations which universally curb all HFT activities and find that the net effect of such policies can be negative. More recently Martin Wheatley, CEO of the Financial Conduct Authority, states that "a priority challenge for HFT specifically, which I'm not sure has yet been honestly assessed by all players, is where the balance lies between the potential benefits against costs."[27] Our study demonstrates that it is important for market regulators to recognize the positive impact of HFT on liquidity provision as documented in our study while assessing the overall costs and benefits of HFT regulation.

[27] "Regulating high frequency trading," Martin Whealey, Financial Conduct Authority, speech on June 4, 2014. URL: http://www.fca.org.uk/news/regulating-high-frequency-trading, accessed on 23 July 2015.

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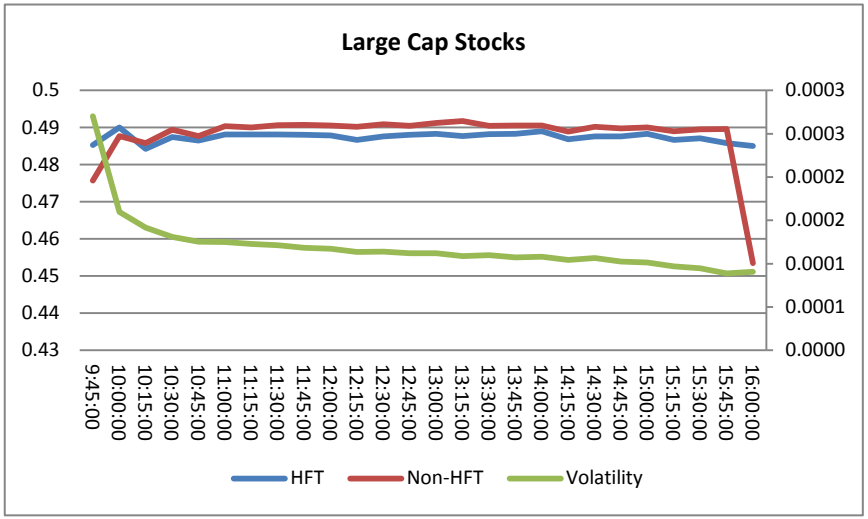
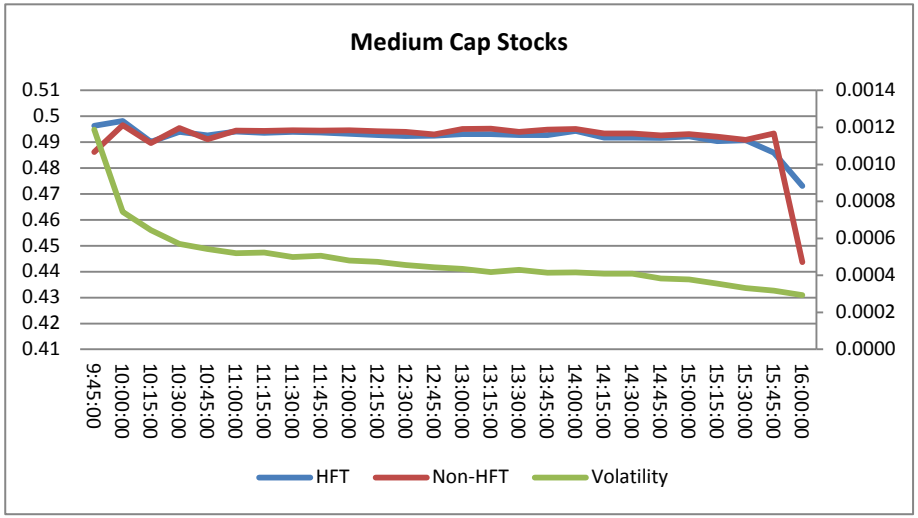
Figure 1: Intraday liquidity cancellation ratio

This figure shows the proportion of limit orders cancelled by HFT and non-HFT firms on the limit order book of the Nasdaq for a sample of 116 stocks listed on the Nasdaq and NYSE over the first quarter of 2011. The sample stocks are sorted by their market capitalizations on January 3, 2011, and divided into large (top 40 stocks), medium (medium 40 stocks), and small (final 36 stocks) size groups. Over the sample period, 26 trading firms are identified as HFT firms and the rest are classified as non-HFT firms. Limit orders submitted and cancelled are aggregated for each 15-minute interval of the trading day. Cancellation ratio is calculated as the total volume cancelled divided by the sum of total volume cancelled and total volume submitted for each interval. Volatility is calculated as the standard deviation of trade returns for each interval.





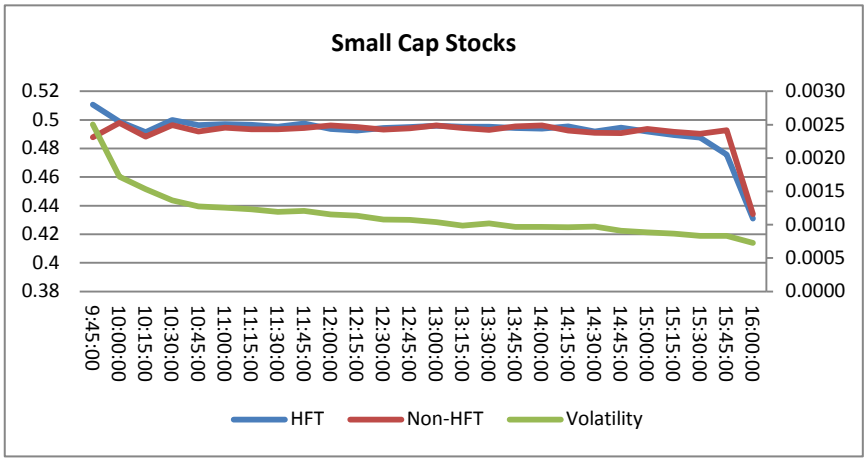
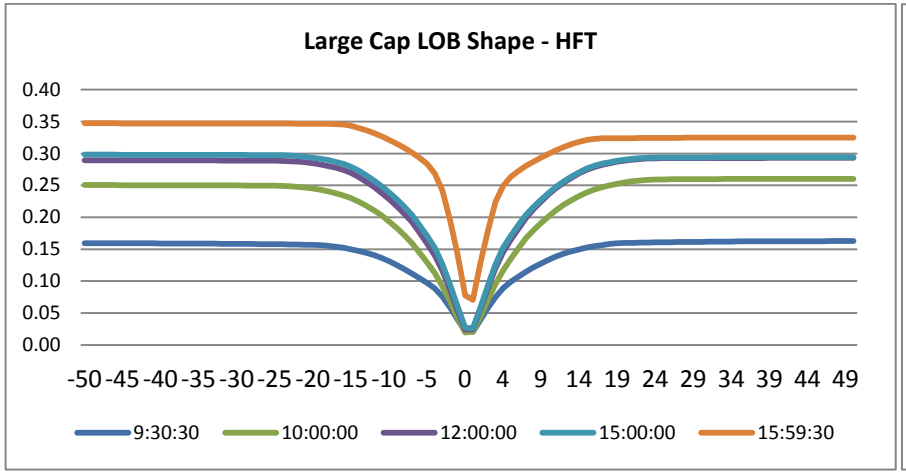
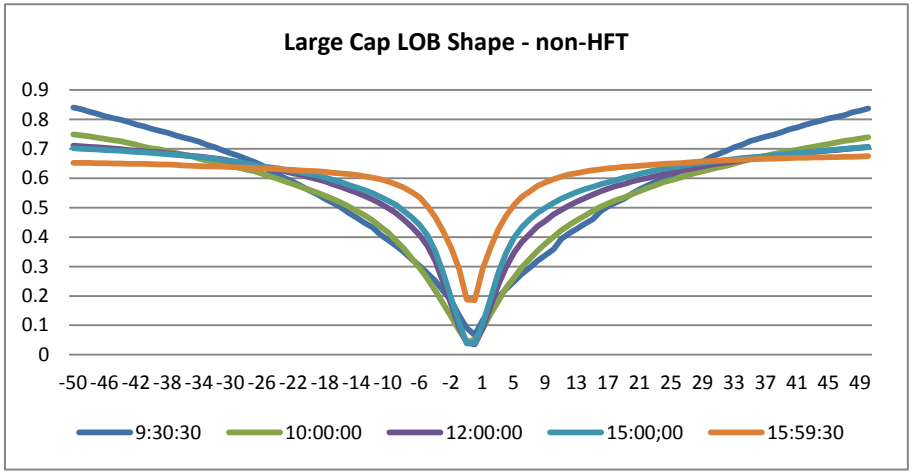
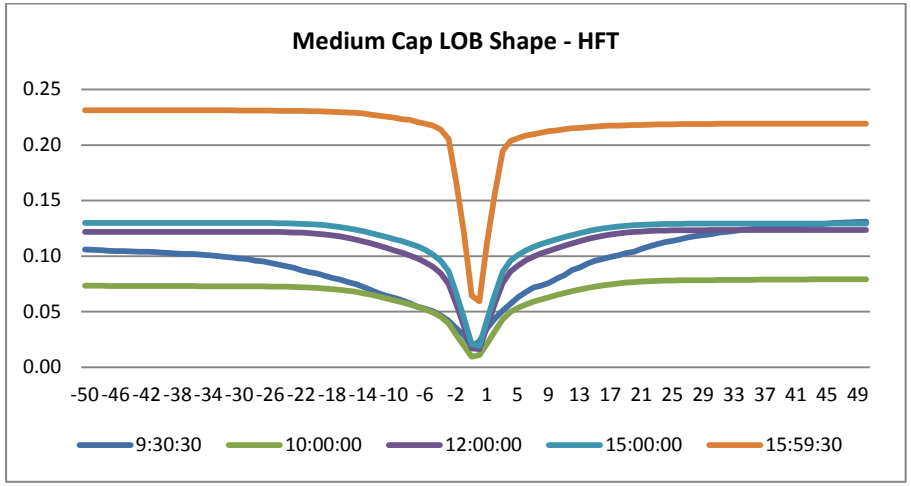


Figure 2: The shape of limit order book: intraday analysis

This figure shows the intraday shape of the LOB on the Nasdaq markets for a sample of 116 stocks listed on the Nasdaq and NYSE over the first quarter of 2011. The sample stocks are sorted by their market capitalization on January 3, 2011, and divided into large (top 40 stocks), medium (medium 40 stocks), and small (final 36 stocks) size groups. Over the sample period, 26 trading firms are identified as HFT firms and the rest are classified as non-HFT firms. For each stock, at the end of each five-second interval, the aggregated depth at each of the top 50 price levels of the LOB is calculated. The average depth contributed by HFT and non-HFT firms at each price level of the LOB is also calculated, and the depicted HFT (non-HFT) LOB shape is the cumulative percentage of limit order volume placed by HFTs (non-HFTs). A zero depth is imposed when there is no order at a particular price level. This figure reports the average HFT and non-HFT LOB shape at 9:30:30, 10:00:00, 12:00:00, 15:00:00, and 15:59:30.






Medium Cap LOB Shape - HFT
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0.15
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0.05
0.00
-50 -46 -42 -38 -34 -30 -26 -22 -18 -14 -10 -6 -2 1 5 9 13 17 21 25 29 33 37 41 45 49
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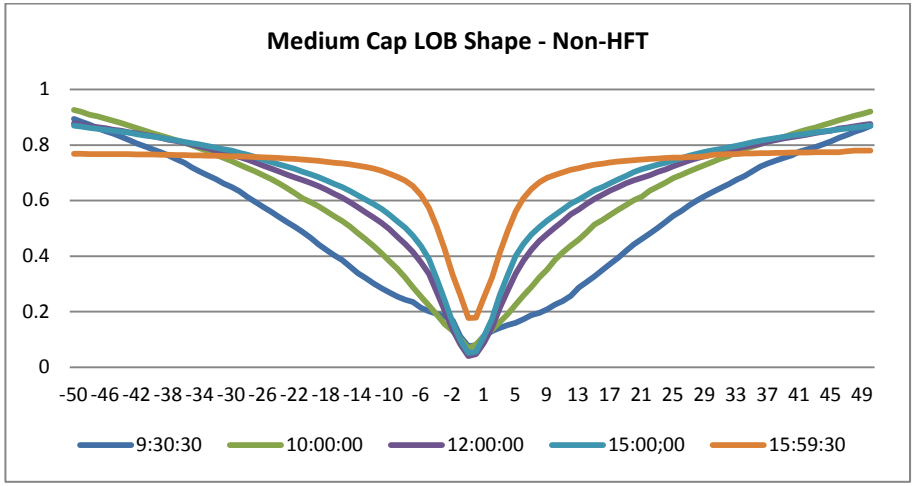
Medium Cap LOB Shape - Non-HFT
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0.6
0.4
0.2
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-50 -46 -42 -38 -34 -30 -26 -22 -18 -14 -10 -6 -2 1 5 9 13 17 21 25 29 33 37 41 45 49
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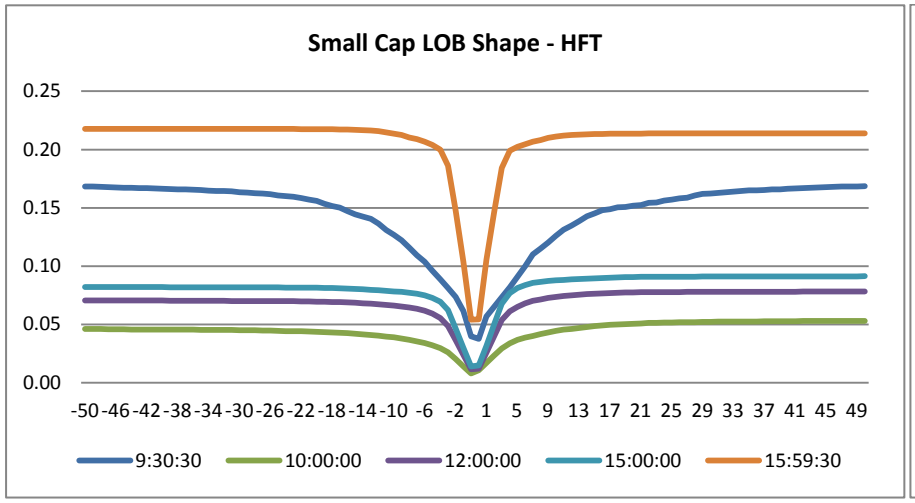
Small Cap LOB Shape - HFT
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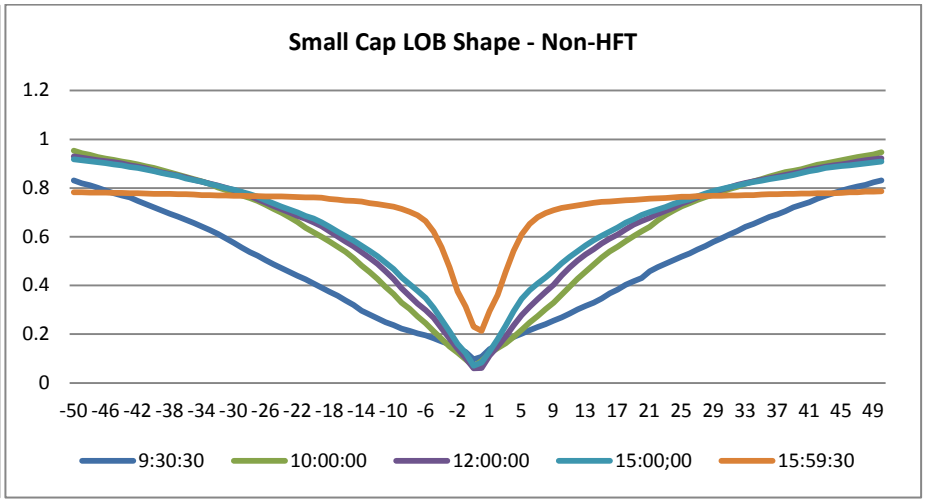
Small Cap LOB Shape - Non-HFT
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15:00;00
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Table 1: Limit order addition, cancellation and execution

This table reports the limit order volume cancelled and submitted by HFT and non-HFT firms on the LOB of the Nasdaq. Order data of 116 stocks listed on the Nasdaq and NYSE are examined over the first quarter of 2011. Twenty-six firms are identified as HFT firms and the rest of traders are classified as non-HFT firms. Each trading day is divided into five-minute intervals. Panel A reports the average limit order volume added, while Panel B reports the average limit order volume cancelled. Panel C reports the limit order cancellation ratio, which is calculated as the average ratio of limit orders cancelled divided by the sum of limit order added and cancelled during a time interval. Panel D reports the execution ratio, which is calculated as the total trading volume divided by the total limit order volume added. Statistics are reported for limit orders submitted to and cancelled from the top 3, 4-10, 11-20, and all top 50 price levels of the LOB. Orders hidden inside the best quotes are included in the top three price levels. *t*-tests are performed to compare the corresponding values between HFT and non-HFT for each category. *, **, and *** indicate statistical significance at the 0.05, 0.01, and 0.001 levels, respectively.

	Top 3		**Top 4 - 10**		**Top 11 - 20**		**All Top 50 Levels**	
	Mean	**Std.**	**Mean**	**Std.**	**Mean**	**Std.**	**Mean**	**Std.**
Panel A: Order addition (shares)								
HFT	67092	182867	15463	50919	2581	19847	85845	235665
Non-HFT	125225	1976398	54258	109830	15019	35699	202463	1996915
Panel B: Order cancellation (shares)								
HFT	62358	167514	15216	51471	2786	20383	81189	222793
Non-HFT	118082	1972498	50799	98982	14929	32800	191575	1990141
Panel C: Cancellation ratio								
HFT	0.4862	0.0706	0.5130	0.1237	0.5678	0.2536	0.4904	0.0480
Non-HFT	0.4858	0.0434	0.5133	0.1210	0.5223	0.1491	0.4905	0.0337
HFT - non-HFT	0.0004	*	-0.0003	***	0.0455	***	-0.0001	
Panel D: Execution ratio								
HFT	0.0529	0.2168					0.0367	0.1179
Non-HFT	0.0733	0.1714					0.0357	0.1493
HFT - non-HFT	-0.0203	***					0.0010	***

Table 2: Comparison of limit order size between HFT and non-HFT firms

This table reports the average size of limit orders submitted and cancelled by HFT and non-HFT firms on the Nasdaq LOB. Order data of 116 stocks listed on the Nasdaq and NYSE are examined over the first quarter of 2011. Twenty-six firms are identified as HFT firms, and the rest are classified as non-HFT firms. For each stock, the average size of limit orders and the averages of size distribution quartiles are reported. The difference in means (medians) between HFT and non-HFT firm are based on a two-tailed *t*-test (Wilcoxon signed rank test). *, **, and *** indicate statistical significance at the 0.05, 0.01, and 0.001 levels, respectively.

	HFT				Non-HFT				Difference			
Tick	**Mean**	**Median**	**Q1**	**Q3**	**Mean**	**Median**	**Q1**	**Q3**	**Mean**		**Median**	
Panel A: Large-cap stocks												
Limit orders submitted												
Top 3	189.44	130.13	100.22	201.98	397.68	138.24	96.37	311.60	-208.24	***	-8.12	***
4 ≤ Level ≤ 10	235.42	147.38	105.58	291.03	350.40	137.91	95.21	378.02	-114.98	***	9.47	***
All top 50	196.36	130.03	100.64	203.25	387.80	136.70	96.98	347.23	-191.44	***	-6.66	***
Limit orders cancelled												
Top 3	187.04	129.88	100.31	196.10	388.29	136.83	98.44	296.82	-201.25	***	-6.95	***
4 ≤ Level ≤ 10	224.94	140.03	104.60	270.87	331.49	134.57	96.31	348.86	-106.55	***	5.46	***
All top 50	193.16	129.14	100.81	197.63	371.03	134.83	97.41	324.85	-177.88	***	-5.68	***
Panel B: Medium-cap stocks												
Limit orders submitted												
Top 3	109.35	99.95	97.07	107.58	233.51	102.11	99.43	165.39	-124.16	***	-2.16	***
4 ≤ Level ≤ 10	140.62	116.65	106.60	151.67	207.37	105.70	99.64	186.43	-66.75	***	10.95	***
All top 50	118.48	100.81	98.49	112.29	242.74	103.87	99.73	210.56	-124.26	***	-3.06	***
Limit orders cancelled												
Top 3	110.84	100.08	97.22	108.75	226.42	102.03	99.61	158.89	-115.58	***	-1.95	***
4 ≤ Level ≤ 10	131.74	110.76	102.71	141.18	193.23	104.82	99.36	171.56	-61.49	***	5.94	***
All top 50	118.46	101.04	98.52	113.19	230.93	103.58	99.72	200.68	-112.46	***	-2.54	***

Table 2: Continued

	HFT				Non-HFT				Difference			
Tick	**Mean**	**Median**	**Q1**	**Q3**	**Mean**	**Median**	**Q1**	**Q3**	**Mean**		**Median**	
Panel C: Small-cap stocks												
Limit orders submitted												
Top 3	130.10	114.32	95.29	143.09	209.52	104.60	100.07	184.74	-79.42	***	9.71	***
$4 \leq$ Level ≤ 10	178.28	144.86	121.62	195.61	218.02	129.59	103.24	230.64	-39.74	***	15.27	***
All top 50	148.12	120.06	99.44	161.22	230.55	112.24	100.06	233.94	-82.43	***	7.82	***
Limit orders cancelled												
Top 3	131.87	116.29	97.68	146.09	201.69	104.32	99.94	176.32	-69.83	***	11.97	***
$4 \leq$ Level ≤ 10	150.45	127.66	107.48	172.56	204.92	122.16	101.94	216.19	-54.47	***	5.50	***
All top 50 levels	146.46	121.25	101.07	162.52	219.09	111.22	100.04	223.98	-72.63	***	10.03	***

Table 3: Comparison of limit order survival time between HFT and non-HFT firms

This table reports the average survival time of limit orders submitted by HFT and non-HFT firms on the Nasdaq markets. Order data of 116 stocks listed on the Nasdaq and NYSE are examined over the first quarter of 2011. Twenty-six trading firms are identified as HFT firms over the sample period, and the rest are classified as non-HFT firms. The survival time of a limit order is calculated as the difference between the time when the order arrives at the LOB and the time the order is terminated. For each stock the volume-weighted average and the median of the survival time are calculated for each trading day, and then averaged. *, **, and *** indicate statistical significance at the 0.05, 0.01, and 0.001 levels, respectively.

	HFT		Non-HFT		Difference			
Tick	**Mean**	**Median**	**Mean**	**Median**	**Mean**		**Median**	
Panel A: Large-cap stocks								
Total survival time								
Top 3	28.74	1.53	37.88	3.02	-9.14	***	-1.49	***
$4 \leq$ Level ≤ 10	96.12	12.48	89.71	14.59	6.40	*	-2.11	***
$11 \leq$ Level ≤ 20	684.47	222.96	291.53	48.94	392.94	***	174.02	***
$21 \leq$ Level ≤ 50	956.34	390.56	718.08	153.77	238.26	***	236.79	***
All levels	39.30	1.85	51.10	4.12	-11.81	***	-2.26	***
Terminated by cancellation - Top 3	28.25	0.53	32.69	3.02	-4.44	***	-2.49	***
Terminated by execution	72.05	3.37	92.53	6.17	-20.48	***	-2.80	***
Panel B: Medium-cap stocks								
Total survival time								
Top 3	33.74	5.20	44.83	5.70	-11.10	***	-0.50	***
$4 \leq$ Level ≤ 10	86.14	16.91	118.34	26.20	-32.20	***	-9.29	***
$11 \leq$ Level ≤ 20	466.51	154.58	195.35	53.44	271.15	***	101.14	***
$21 \leq$ Level ≤ 50	292.81	93.19	353.69	88.83	-60.88	***	4.35	***
All levels	40.62	6.02	70.45	8.98	-29.83	***	-2.96	***
Terminated by cancellation - Top 3	30.32	2.15	34.33	3.47	-4.01	***	-1.32	***
Terminated by execution	67.30	9.59	97.67	12.50	-30.37	***	-2.91	***
Panel C: Small-cap stocks								
Total survival time								
Top 3	51.89	18.04	81.81	17.82	-29.93	***	0.22	***
$4 \leq$ Level ≤ 10	90.06	20.65	202.97	48.01	-112.92	***	-27.36	***
$11 \leq$ Level ≤ 20	181.43	91.24	278.66	64.38	-97.22	***	26.86	***
$21 \leq$ Level ≤ 50	174.60	125.05	583.13	152.77	-408.53	***	-27.72	***
All levels	55.71	18.30	124.24	22.43	-68.53	***	-4.12	***
Terminated by cancellation - Top 3	46.16	6.84	40.90	4.48	5.26	***	2.36	
Terminated by execution	101.94	38.28	201.98	41.14	-100.04	***	-2.87	***

Table 4: Distribution of limit orders placed by HFT firms on the LOBs

This table reports the percentage of limit orders placed by HFT firms on the LOB. Order data of 116 stocks listed on the Nasdaq and NYSE are examined for the first quarter of 2011. Twenty-six HFT firms are identified. A snapshot of the LOB is taken at the end of every five-second interval between 9:30:30 and 16:00. At each price level of the LOB, the percentage of HFT volume is calculated as the total volume of limit orders submitted by HFT firms divided by the total volume of all limit orders at this price level. *Tick* measures the number of ticks between the current bid (ask) price and the best bid (ask) price. Orders hidden inside the best quotes are included in the Tick 0 category. The results for the top 50 price levels are reported. For each five-second time interval, the absolute values of the bid-ask midpoint log returns are calculated and sorted for each stock. A time interval is classified as high, medium or low risk if the absolute return of the interval falls into the top 1%, between 90% – 99%, and below 90% levels of the distribution, respectively.

	Buy					Sell			
Tick	High Risk	Medium Risk	Low Risk	All	Tick	High Risk	Medium Risk	Low Risk	All
Panel A: Large-cap stocks									
0	44.80%	43.87%	37.38%	42.25%	0	45.76%	44.35%	37.60%	42.82%
1	46.42%	41.17%	37.78%	41.99%	1	46.90%	41.26%	37.92%	42.23%
2	40.67%	32.87%	28.49%	34.29%	2	40.88%	32.90%	28.44%	34.36%
3	37.71%	29.57%	24.47%	30.89%	3	37.92%	29.84%	24.77%	31.15%
4	36.02%	28.16%	23.20%	29.43%	4	36.16%	28.76%	23.66%	29.82%
5	35.53%	28.75%	23.70%	29.61%	5	35.78%	29.42%	24.31%	30.12%
10	30.26%	28.23%	24.02%	27.68%	10	29.96%	28.49%	24.70%	27.87%
20	16.97%	18.52%	16.90%	17.49%	20	16.31%	18.09%	16.58%	17.01%
50	2.74%	1.49%	1.35%	1.87%	50	2.84%	1.51%	1.37%	1.92%
Panel B: Medium-cap stocks									
0	36.62%	34.78%	27.53%	33.31%	0	37.72%	35.01%	28.12%	33.96%
1	41.22%	39.57%	38.22%	39.76%	1	41.96%	39.60%	38.23%	40.04%
2	35.53%	33.24%	31.43%	33.52%	2	36.20%	33.13%	31.05%	33.61%
3	31.21%	27.87%	27.93%	29.07%	3	31.45%	27.84%	27.18%	28.92%
4	24.96%	22.12%	23.68%	23.57%	4	24.96%	21.97%	23.32%	23.42%
5	20.47%	17.37%	17.96%	18.64%	5	20.63%	17.47%	18.24%	18.81%
10	11.92%	12.61%	7.14%	10.77%	10	11.91%	13.03%	7.44%	11.00%
20	9.04%	10.22%	4.32%	8.07%	20	9.56%	10.53%	4.31%	8.36%
50	0.82%	0.56%	0.65%	0.67%	50	0.79%	0.57%	0.60%	0.65%
Panel C: Small-cap stocks									
0	25.69%	23.47%	20.29%	23.34%	0	26.25%	24.02%	20.56%	23.82%
1	30.07%	29.97%	29.16%	29.77%	1	29.73%	29.76%	29.29%	29.62%
2	28.99%	29.98%	28.23%	29.12%	2	29.29%	29.96%	27.96%	29.15%
3	27.80%	29.23%	28.67%	28.57%	3	28.18%	29.69%	29.02%	28.97%
4	23.22%	24.44%	28.01%	25.05%	4	24.10%	25.34%	28.77%	25.90%
5	17.37%	17.84%	21.32%	18.68%	5	17.54%	17.88%	21.34%	18.76%
10	6.83%	6.49%	6.75%	6.69%	10	7.05%	6.72%	7.03%	6.92%
20	3.10%	3.11%	3.27%	3.16%	20	3.20%	3.64%	3.58%	3.47%
50	0.71%	1.07%	1.37%	1.05%	50	0.91%	0.99%	1.33%	1.07%

Table 5: Limit order book slope and price volatility

This table reports estimates of Eq. (4):

$$R_t = \sum_{n=1}^{12} R_{t-n} + \sum_{m=2}^{26} D_m + \varepsilon_t.$$

$$|\varepsilon_t| = \sum_{n=1}^{12} |\varepsilon_{t-n}| + \sum_{m=2}^{26} D_m + \sum_{j=2}^{116} D_j + Turnover_T + MktCap_T + \frac{1}{P_T} + Size_t + Trades_t + Slope_{t-1}^{HFT} +$$

$$Slope_{t-1}^{Non-HFT} + Depth_{t-1} + \eta_t.$$

Order data on the Nasdaq markets of 116 stocks listed on the Nasdaq and NYSE are examined over the first quarter of 2011. Twenty-six HFT firms are identified and the rest are non-HFT traders firms. Each trading day is divided into five-second time intervals from 9:30:30 to 16:00:00. R_t is the bid-ask midpoint return for interval t. D_j are stock dummy variables. Each trading day is further divided into 26 15-minute intervals with the first interval ending at 9:45:00, and D_m are dummy variables for these intervals. $Turnover_T$, $MktCap_T$, and P_T are the share turnover, market capitalization, and average trade price for the current stock on day T. Size_t and Trades_t are the average trade size and the number of trades at interval t, respectively. $Depth_t$ is the total limit order volume available at particular price levels. $Slope_t$ is the slope of the LOB at the end of interval t and is calculated as:

$$Slope_t = \frac{1}{N}\left(\frac{v_1}{\left|\frac{p_1}{p_0}-1\right|} + \sum_{n=1}^{N} \frac{v_{n+1}-v_n}{\left|\frac{p_{n+1}}{p_n}-1\right|}\right),$$

where p_n and v_n are the price and volume at the n^{th} price level, respectively. $Slope_t^{HFT}$ and $Slope_t^{Non-HFT}$ are the slope variables constructed using HFT and non-HFT limit orders only. The limit order volume is normalized by the total shares outstanding of the current stock. p_0 is the bid-ask midpoint. Orders on the top 50 price levels of the LOB are examined. Standard errors are corrected for heteroscedasticity following White (1980). Except for the return, slope, and dummy variables, all variables are log transformed. The coefficients and standard errors are enlarged by 10^6 for the depth variable, and enlarged by 10^4 for all the other variables. *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

Variables (lagged)	Large Cap Coeff.	Large Cap Std. Err.		Medium Cap Coeff.	Medium Cap Std. Err.		Small Cap Coeff.	Small Cap Std. Err.	
Intercept	2.9384	0.0274	***	-0.9707	0.8444		7.5591	0.3890	***
Turnover	0.0292	0.0016	***	0.0019	0.0047		0.0142	0.0009	***
Market cap.	0.0021	0.0014		0.1229	0.0000	***	0.8983	0.0283	***
Inverse price	15.4000	0.1302	***	4.7932	0.6329	***	-0.0207	0.0044	***
Trade size	0.0018	0.0000	***	0.0084	0.0010	***	-0.2257	0.0193	***
Number of trades	0.0785	0.0008	***	0.3671	0.0114	***	-1.5057	0.1997	***
Total depth									
Top 3	-22.3800	0.1168	***	-14.8200	0.2029	***	-12.6900	0.4872	***
$4 \leq$ Level ≤ 10	-9.5500	0.1476	***	3.0100	0.2564	***	5.3600	0.6661	***
$11 \leq$ Level ≤ 20	-3.0200	0.1087	***	-3.4200	0.2589	***	-12.3300	0.7108	***
$21 \leq$ Level ≤ 50	0.2700	0.0676	***	-1.0200	0.0952	***	-1.1000	0.2030	***
LOB slope									
HFT									
Top 3	-2.4358	0.1974	***	-18.5000	0.8200	***	-31.7000	4.2347	***
$4 \leq$ Level ≤ 10	-37.0000	0.8978	***	-25.4000	1.7601	***	-117.1000	14.0000	***
$11 \leq$ Level ≤ 20	-17.1000	1.5462	***	-41.5000	5.5773	***	-99.7000	44.9000	*
$21 \leq$ Level ≤ 50	-0.2305	0.7645		-7.3294	3.4126	*	27.9000	16.6000	
Non-HFT									
Top 3	0.2261	0.0099	***	-0.9342	0.0469	***	-1.5344	0.1174	***
$4 \leq$ Level ≤ 10	-0.8896	0.0415	***	-1.9413	0.1035	***	-5.0561	0.4228	***
$11 \leq$ Level ≤ 20	-1.0257	0.0874	***	-0.3072	0.1883		-0.2066	0.5364	
$21 \leq$ Level ≤ 50	-0.2482	0.0431	***	-0.0253	0.0241		0.0277	0.1137	
H0: HFT = Non-HFT									
Top 3		178.53	***		472.57	***		50.04	***
$4 \leq$ Level ≤ 10		1603.57	***		179.69	***		63.73	***
$11 \leq$ Level ≤ 20		107.53	***		54.58	***		4.91	*
$21 \leq$ Level ≤ 50		0.00			4.58	*		2.83	

Table 6: Relation between future returns and order addition and cancellation

This table reports estimates of the regression model:

$$R_t = \sum_{i=1}^{12} R_{t-i} + \sum_{m=2}^{26} D_m + \sum_{j=2}^{40} D_j + Turnover_T + MktCap_T + \frac{1}{P_T} + Size_t^{Buy} + Size_t^{Sell} + Trades_t^{Buy} + Trades_t^{Sell} + Order\_added_{t-1}^{HFT\_buy} + Order\_added_{t-1}^{HFT\_sell} + Order\_added_{t-1}^{Non-HFT\_buy} + Order\_added_{t-1}^{Non-HFT\_sell} + Order\_cancelled_{t-1}^{HFT\_buy} + Order\_cancelled_{t-1}^{HFT\_sell} + Order\_cancelled_{t-1}^{Non-HFT\_buy} + Order\_cancelled_{t-1}^{Non-HFT\_sell} + \varepsilon_t.$$

Order data on the Nasdaq markets for a total of 116 stocks listed on the Nasdaq and NYSE are examined for the first quarter of 2011. Twenty-six trading firms are identified as HFT traders over the sample period, and the rest of traders are classified as non-HFT traders. Each trading day is divided into five-second intervals from 9:30:30 to 16:00:00, and R_t is the bid-ask midpoint return for interval t. D_m are stock dummy variables. Each trading day is further divided into 26 15-minute intervals with the first interval ending at 9:45:00, and D_j are time dummy variables representing these time intervals. $Turnover_T$, $MktCap_T$ and P_T are share turnover, market capitalization, and average trade price for the current stock on day T. $Size_t^{Buy}$ ($Size_t^{Sell}$), and $Trades_t^{Buy}$ ($Trades_t^{Sell}$) are the average size of buyer- (seller-) initiated trades and the number of buyer- (seller-) initiated trades during interval t, respectively. $Order\_added_t^{HFT\_buy}$ ($Order\_added_t^{HFT\_sell}$), and $Order\_added_t^{Non-HFT\_buy}$ ($Order\_added_t^{Non-HFT\_sell}$) are the total buy (sell) limit order volume submitted during interval t, respectively. Similarly, $Order\_cancelled_t^{HFT\_buy}$ ($Order\_cancelled_t^{HFT\_sell}$), and $Order\_cancelled_t^{Non-HFT\_buy}$ ($Order\_cancelled_t^{Non-HFT\_sell}$) are the total buy (sell) limit order volume cancelled during interval t, respectively. Orders submitted to the top three price levels of the LOB are examined. Except for the dummy and return variables, all variables are log transformed. Standard errors are corrected for heteroscedasticity using White (1980). R_t is enlarged by 10^6 in model estimation to avoid loss of precision in calculation. *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

	Large-Cap			Medium-Cap			Small-Cap		
	Coeff.	**Std. Err.**		**Coeff.**	**Std. Err.**		**Coeff.**	**Std. Err.**	
Intercept	11.1639	1.7075	***	-21.7324	6.7814	**	-224.2806	119.2516	
Size - buy	3.9304	0.0481	***	35.2217	0.1968	***	81.1214	0.7057	***
Size - sell	-4.0345	0.0491	***	-35.9279	0.1965	***	-78.9022	0.6903	***
# of trades - buy	121.7346	0.2030	***	224.7282	1.3488	***	346.2010	6.2162	***
# of trades - sell	-123.5578	0.2039	***	-224.3631	1.3231	***	-342.2134	5.8669	***
Turnover	0.0952	0.0802		-0.1344	0.1021		0.2770	0.3115	
Market capitalization	-0.3807	0.0779	***	0.9691	0.3145	**	10.2000	5.5544	
Inverse price	-29.8366	4.9335	***	2.8269	4.2055		117.0374	79.1118	
Liquidity addition									
HFT buy	0.6427	0.0226	***	1.3595	0.0462	***	3.0955	0.1163	***
Non-HFT buy	0.9675	0.0184	***	1.8493	0.0320	***	3.6457	0.0722	***
H0: HFT buy = non-HFT buy		114.34	***		73.48	***		16.49	***
HFT sell	-0.6516	0.0224	***	-1.3024	0.0460	***	-2.9992	0.1154	***
Non-HFT sell	-0.9211	0.0184	***	-1.7453	0.0313	***	-3.7080	0.0721	***
H0: HFT sell = non-HFT sell		79.37	***		61.63	***		27.27	***
Liquidity cancellation									
HFT buy	-0.1483	0.0221	***	-0.4368	0.0461	***	-1.3806	0.1161	***
Non-HFT buy	0.1141	0.0177	***	-0.2804	0.0313	***	-0.7127	0.0712	***
H0: HFT buy = non-HFT buy		74.37	***		7.26	**		22.69	***
HFT sell	0.2011	0.0219	***	0.4604	0.0455	***	1.4521	0.1145	***
Non-HFT sell	-0.0671	0.0178	***	0.3710	0.0306	***	0.9416	0.0712	***
H0: HFT sell = non-HFT sell		78.20	***		2.43			13.51	***

Table 7: Adverse selection costs for liquidity providers in transactions

This table reports the adverse selection costs incurred by HFT and non-HFT firms when they provide liquidity in transactions. Transaction data on the Nasdaq markets for 116 stocks listed on the Nasdaq and NYSE are examined for the first quarter of 2011. Twenty-six HFT firms are identified and the rest are non-HFT firms. All transactions on the Nasdaq markets are sorted by trade size for each stock over the sample period, and transactions falling into the top 5%, between 50% and 95% and the bottom 50% of the trade size distribution are classified as small, medium and large trades, respectively. The adverse selection costs of limit orders executed in transactions are calculated as:

$$Adverse\ selection\ cost_t = q_t \frac{(m_{t+n} - m_t)}{m_t}, \quad (6)$$

where m_t and m_{t+n} are the NBBO midpoint at time t and n seconds, respectively, after time t, and q_t is a buy (sell) indicator, which equals to -1 (1) if it is a buy (sell) trade. For each stock day, the volume-weighted average adverse selection costs for liquidity provided by HFTs and non-HFTs in transactions are calculated over a 30-second (short-term) and 180-second (long-term) period. The adverse selection costs reported are expressed in basis points. *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

	Short-term					Long-term				
Trade Size	**HFT**	**Non-HFT**	**HFT - Non-HFT**	***t*-stat**		**HFT**	**Non-HFT**	**HFT - Non-HFT**	***t*-stat**	
Panel A: Large stocks										
Small	1.3763	2.0090	-0.6327	-19.83	***	1.3511	1.9655	-0.6144	-13.9	***
Medium	1.6371	2.1170	-0.4799	-14.53	***	1.6802	2.0674	-0.3872	-9.76	***
Large	1.9081	2.5328	-0.6248	-11.40	***	1.9492	2.5080	-0.5588	-7.37	***
Panel B: Medium stocks										
Small	2.2419	2.9230	-0.6812	-8.86	***	2.4977	2.9634	-0.4657	-3.84	***
Medium	2.9193	3.4039	-0.4846	-7.33	***	3.2847	3.5110	-0.2263	-2.32	*
Large	4.1316	4.1770	-0.0455	-0.22		4.4529	4.3893	0.0636	0.21	
Panel C: Small stocks										
Small	3.8453	4.0724	-0.2270	-0.83		4.2858	4.4463	-0.1606	-0.46	
Medium	5.2408	5.6933	-0.4524	-2.06	*	5.8195	6.0778	-0.2583	-0.88	
Large	6.9985	7.2202	-0.2217	-0.41		6.7535	8.1269	-1.3734	-1.97	*

Table 8: Opportunity costs of limit orders submitted and cancelled

This table reports the opportunity costs of HFT and non-HFT firms at the time of submitting or cancelling a limit order on the Nasdaq markets. Limit order opportunity cost is calculated as:

$$Opportunity\ cost_t = q_t \frac{(m_{t+n} - m_t)}{m_t}, \quad (1)$$

where m_t and m_{t+n} are the NBBO midpoint at time t and n seconds, respectively, after time t, and p_t is the price of the limit order. q_t is a buy sell indicator, which equals to 1 (-1) if the order is buyer- (seller-) initiated. Order data on the Nasdaq markets for 116 stocks listed on the Nasdaq and NYSE are examined for the first quarter of 2011. Twenty-six HFT firms are identified and the rest are non-HFT firm. The sample stocks are sorted by their market capitalization on January 1, 2011, and divided into large (top 40 stocks), medium (medium 40 stocks), and small (final 36 stocks) size groups. For each stock day, all limit orders submitted are sorted by order size, and a limit order submitted or cancelled is classified as a small, medium or large order if the order size falls into the top 5%, between 50% and 95%, and the bottom 50% levels of the size distribution, respectively. For each stock day, the volume-weighted average opportunity costs are calculated for limit orders submitted (Panel A) and for limit orders cancelled (Panel B) at the top three price levels of the LOB over a 30-second (short-term) and 180-second (long-term) period. Opportunity costs reported are in basis points. The percentage of limit orders submitted (cancelled) at the top three price levels of the LOB is also reported. Panel C shows the differences in opportunity costs between HFT and non-HFT firms for orders submitted (Panel A), as well as the differences in opportunity costs between HFT and non-HFT firms for orders cancelled (Panel B). *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

	Short-term					Long-term					% of Orders	
Order Size	**HFT**	**Non-HFT**	**HFT - Non-HFT**	***t*-stat**		**HFT**	**Non-HFT**	**HFT - Non-HFT**	***t*-stat**		**HFT**	**Non-HFT**
Panel A: Opportunity costs of limit orders added												
Large-cap stocks												
Small	0.8499	0.6511	0.2011	14.32	***	0.8747	0.7018	0.1792	8.82	***	79	67
Medium	1.1789	0.7987	0.3814	19.13	***	1.1762	0.8731	0.2989	8.81	***	21	26
Large	1.2958	0.9164	0.3865	8.30	***	1.2340	1.4297	-0.1689	-1.93		1	7
Medium-cap stocks												
Small	1.0428	0.7777	0.2651	9.59	***	1.2097	0.9556	0.2538	5.46	***	93	73
Medium	1.0934	0.9707	0.1224	1.76		1.0905	1.4134	-0.3105	-2.23	*	7	22
Large	0.9593	1.4340	-0.5857	-2.72	**	1.3546	2.4868	-1.3277	-3.55	***	1	5
Small-cap stocks												
Small	1.4758	1.4512	0.0231	0.21		1.8448	2.1745	-0.3175	-2.60	**	87	71
Medium	1.5074	2.0961	-0.5866	-3.91	***	1.4689	3.0134	-1.5594	-5.27	***	12	25
Large	0.9871	2.4786	-1.8134	-6.02	***	1.1193	3.6584	-2.8408	-5.77	***	4	4
Panel B: Opportunity costs of limit orders cancelled												
Large-cap stocks												
Small	0.0370	0.1747	-0.1376	-15.21	***	0.0441	0.1967	-0.1522	-9.85	***	79	68
Medium	0.0978	0.1740	-0.0770	-5.40	***	0.0845	0.1947	-0.1122	-3.62	***	21	26
Large	0.0739	0.4590	-0.3757	-8.32	***	0.0570	0.8938	-0.7941	-7.85	***	1	7
Medium-cap stocks												
Small	0.0663	0.3034	-0.2374	-9.18	***	0.1849	0.4483	-0.2670	-6.11	***	92	74
Medium	0.0857	0.4283	-0.3420	-5.05	***	0.0446	0.8066	-0.7494	-5.21	***	8	22
Large	0.0377	0.9899	-0.9852	-5.16	***	0.3600	1.9817	-1.7316	-4.28	***	1	5
Small-cap stocks												
Small	0.1279	0.6988	-0.5602	-7.45	***	0.3698	1.2874	-0.9100	-6.72	***	86	72
Medium	0.3343	1.2725	-0.9161	-5.78	***	0.1547	2.1037	-1.9320	-6.45	***	13	25
Large	0.9277	1.7412	-1.1835	-2.68	**	1.5737	2.7965	-1.6366	-2.27	*	4	3

Table 8 Continued

	Short-term					Long-term					% of Orders	
Order Size	**HFT**	**Non-HFT**	**HFT - Non-HFT**	***t*-stat**		**HFT**	**Non-HFT**	**HFT - Non-HFT**	***t*-stat**		**HFT**	**Non-HFT**
Panel C: Difference-in-differences												
Large-cap stocks												
Small			0.3403	30.10	***			0.3344	16.75	***		
Medium			0.4636	25.39	***			0.4238	9.92	***		
Large			0.7634	11.99	***			0.6645	4.33	***		
Medium-cap stocks												
Small			0.5024	14.40	***			0.5201	8.94	***		
Medium			0.4934	5.15	***			0.4833	2.24	*		
Large			0.4447	1.56				0.2277	0.82			
Small-cap stocks												
Small			0.5772	5.92	***			0.5866	3.30	***		
Medium			0.2655	1.58				0.3250	0.94			
Large			-0.6870	-1.51				-0.9006	-1.70			

Table 9 Relative spreads and limit order opportunity costs

This table reports the relative spreads and the opportunity costs of limit orders placed at the NBBO price levels on the Nasdaq markets. Relative spreads are calculated based on the NBBO prices immediately before the limit order arrives on the market. The long- and short-term opportunity costs are as defined in Table 8. Order data on the Nasdaq markets for 116 stocks listed on the Nasdaq and NYSE are examined for the first quarter of 2011. Twenty-six HFT firms are identified and the rest are non-HFT firms. The sample stocks are sorted by their market capitalization on January 1, 2011, and divided into large (top 40 stocks), medium (medium 40 stocks), and small (final 36 stocks) size groups. Only orders placed at the NBBO price levels are considered. For each stock day, all limit orders submitted are sorted by order size, and a limit order submitted or cancelled is classified as a small, medium or large order if the order size falls into the top 5%, between 50% and 95%, and the bottom 50% levels of the size distribution, respectively. Relative spreads an opportunity costs are in basis points. *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

				Opportunity Costs - Relative Spreads					
		Opportunity Costs		Short-term			Long-term		
Order Size	Relative Spreads	Short-term	Long-term	Mean	*t*-stat		Mean	*t*-stat	
Section A: HFT limit orders									
Panel I: Large-cap stocks									
Small	3.6376	1.0480	1.0834	-2.5896	-64.03	***	-2.554	-60.21	***
Median	3.6701	1.3773	1.3683	-2.2928	-49.80	***	-2.302	-44.96	***
Large	3.8599	1.5540	1.5431	-2.3059	-29.17	***	-2.317	-18.43	***
Panel II: Medium-cap stocks									
Small	10.0950	1.2916	1.5782	-8.8035	-66.40	***	-8.517	-46.67	***
Median	10.2744	1.3138	1.2205	-8.9607	-62.03	***	-9.054	-42.19	***
Large	18.7465	1.1307	1.3768	-17.6159	-23.13	***	-17.370	-20.89	***
Panel III: Small-cap stocks									
Small	30.5576	1.9869	2.3968	-28.5707	-51.88	***	-28.161	-49.81	***
Median	30.5898	1.8197	1.9706	-28.7701	-47.53	***	-28.619	-43.64	***
Large	44.9008	1.4574	1.5816	-43.4434	-34.57	***	-43.319	-32.71	***
Section B: Non-HFT limit orders									
Panel I: Large-cap stocks									
Small	3.6216	0.8307	0.9013	-2.7909	-65.68	***	-2.720	-58.73	***
Median	3.6665	1.1239	1.2256	-2.5425	-56.51	***	-2.441	-43.69	***
Large	3.7799	1.5112	2.3858	-2.2688	-42.92	***	-1.394	-17.44	***
Panel II: Medium-cap stocks									
Small	10.8566	0.9707	1.1510	-9.8858	-80.80	***	-9.706	-70.84	***
Median	11.0536	1.2634	1.7420	-9.7902	-68.19	***	-9.312	-52.29	***
Large	11.9996	1.7672	2.9735	-10.2324	-68.71	***	-9.026	-42.78	***
Panel III: Small-cap stocks									
Small	31.3141	1.6804	2.4258	-29.6337	-76.32	***	-28.888	-70.61	***
Median	32.4906	2.3507	3.3866	-30.1400	-74.05	***	-29.104	-66.67	***
Large	31.3606	2.8518	4.1828	-28.5089	-65.95	***	-27.178	-58.31	***

Table 10 Net liquidity provision

This table reports the estimates of regression:

$$Net\_liquidity_t = D_{HFT} + \sum_{m=2}^{26} D_m + \sum_{j=2}^{40} D_j + Turnover_T + \frac{1}{P_T} + Size_t + Trades_t + Volatility_{t-1} + D_{HFT} \times Volatility_{t-1} + D_{x\_vola} + D_{x\_vola} \times D_{HFT} + \varepsilon_t.$$

Each trading day is divided into 30-second intervals. $Net\_liquidity_t$ is the net liquidity provided by HFT and non-HFT firms during interval t. The net liquidity is calculated as the difference between total limit order volume submitted and total limit order volume cancelled. Limit orders within five ticks from the Nasdaq BBO prices are considered. D_{HFT} is a dummy variable that equals 1 if the current net liquidity observation is for a HFT firm, or 0 otherwise. $Volatility_t$ is the standard deviation of second-by-second bid-ask midpoint returns during interval t. For each stock, $Volatility_t$ is sorted for the sample period and D_{x_vola} equals 1 if the current volatility falls into the largest 1% of the volatility distribution. All other variables are defined as in Table 5. Except for the dummy variables, all variables are standardized by stock. Standard errors are corrected for heteroscedasticity using White (1980). *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

	Large-Cap Stocks			**Medium-Cap Stocks**			**Small Cap-Stocks**		
	Coeff.	**Std. Err.**		**Coeff.**	**Std. Err.**		**Coeff.**	**Std. Err.**	
Intercept	0.3176	0.0057	***	0.0840	0.0082	***	0.0267	0.0137	
Size	0.0165	0.0008	***	0.0020	0.0021		-0.0021	0.0022	
# of trades	0.1450	0.0021	***	0.0480	0.0029	***	0.0323	0.0030	***
Turnover	0.0751	0.0008	***	0.0464	0.0013	***	0.0263	0.0019	***
Inverse price	-0.0284	0.0018	***	-0.0231	0.0071	**	-0.0228	0.0077	**
Volatility	-0.1021	0.0020	***	0.0025	0.0030		0.0361	0.0035	***
D_{HFT}	-0.0169	0.0011	***	-0.0022	0.0020		0.0033	0.0034	
D_{HFT} *x Volatility*	0.1111	0.0023	***	0.0245	0.0039	***	-0.0047	0.0120	
D_{x_vola}	0.2765	0.0156	***	0.0738	0.0205	***	-0.0047	0.0298	
D_{x_vola} *x* D_{HFT}	0.1652	0.0227	***	0.0248	0.0338		0.0479	0.0759	

Table 11 Order imbalances and limit order book slope

This table reports estimates of the equation:

$$Slope_t = \sum_{j=2}^{116} D_j + \sum_{m=1}^{10} Resi\_OI_{t-i} + D_{HFT} + \sum_{n=1}^{10} D_{HFT} \times Resi\_OI_{t-n} \quad (1)$$

Order data on the Nasdaq markets of 116 stocks listed on the Nasdaq and NYSE are examined for the first quarter of 2011. Twenty-six HFT trading firms are identified and the rest are non-HFT firms. Each trading day is divided into 10-second intervals. $Slope_t$ is the slope of the LOB at the end of each interval, which is calculated by using buy or sell limit orders separately (see Table 5 for details). D_j are stock dummy variables. $Resi\_OI_t$ is the liquidity imbalance variable, which is estimated as the residuals of the regression:

$$OI_t = \sum_{m=1}^{10} OI_{t-i} + \eta_t.$$

For each time interval, the net buy (sell) limit order volume is the difference between total buy (sell) limit order volume submitted and total buy (sell) limit order volume cancelled, while OI_t is the difference between the net buy limit order volume and the net sell limit order volume. D_{HFT} is a dummy variable that equals 1 if the current $Slope_t$ is constructed by using limit orders of HFT firms, and 0 otherwise. Orders at the top 10 price levels are examined. All variables are standardized by stock except for the dummy variables. Standard errors are corrected for heteroscedasticity following White (1980). *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

	Large-Cap Stocks			**Medium-Cap Stocks**			**Small-Cap Stocks**		
	Coeff.	**Std. Err.**		**Coeff.**	**Std. Err.**		**Coeff.**	**Std. Err.**	
Panel A: LOB buy slope									
Intercept	0.0033	0.0020		0.0627	0.0041	***	0.6884	0.0234	***
D_{HFT}	0.0134	0.0006	***	0.0543	0.0017	***	0.3080	0.0096	***
Resi_OI_lag1	0.0424	0.0036	***	0.0405	0.0041	***	0.0953	0.0343	**
Resi_OI_lag2	0.0327	0.0018	***	0.0341	0.0039	***	0.1066	0.0345	**
Resi_OI_lag3	0.0298	0.0018	***	0.0309	0.0041	***	0.0549	0.0140	***
Resi_OI_lag4	0.0261	0.0018	***	0.0284	0.0051	***	0.0448	0.0136	***
Resi_OI_lag5	0.0246	0.0017	***	0.0242	0.0038	***	0.0462	0.0133	***
Resi_OI_lag6	0.0200	0.0017	***	0.0249	0.0037	***	0.0618	0.0143	***
Resi_OI_lag7	0.0169	0.0015	***	0.0244	0.0043	***	0.0404	0.0106	***
Resi_OI_lag8	0.0167	0.0016	***	0.0224	0.0041	***	0.0480	0.0123	***
Resi_OI_lag9	0.0142	0.0014	***	0.0155	0.0031	***	0.0510	0.0216	*
Resi_OI_lag10	0.0144	0.0015	***	0.0098	0.0029	***	0.0545	0.0328	
D_{HFT} *x Resi_OI_lag1*	-0.0050	0.0037		-0.0128	0.0046	**	-0.0776	0.0359	*
D_{HFT} *x Resi_OI_lag2*	-0.0089	0.0020	***	-0.0146	0.0042	***	-0.0868	0.0359	*
D_{HFT} *x Resi_OI_lag3*	-0.0137	0.0020	***	-0.0153	0.0044	***	-0.0438	0.0164	**
D_{HFT} *x Resi_OI_lag4*	-0.0141	0.0019	***	-0.0162	0.0054	**	-0.0390	0.0159	*
D_{HFT} *x Resi_OI_lag5*	-0.0155	0.0019	***	-0.0140	0.0042	***	-0.0508	0.0155	**
D_{HFT} *x Resi_OI_lag6*	-0.0123	0.0019	***	-0.0157	0.0040	***	-0.0595	0.0166	***
D_{HFT} *x Resi_OI_lag7*	-0.0104	0.0017	***	-0.0172	0.0045	***	-0.0310	0.0133	*
D_{HFT} *x Resi_OI_lag8*	-0.0100	0.0017	***	-0.0161	0.0043	***	-0.0362	0.0144	*
D_{HFT} *x Resi_OI_lag9*	-0.0090	0.0016	***	-0.0076	0.0035	*	-0.0515	0.0229	*
D_{HFT} *x Resi_OI_lag10*	-0.0095	0.0016	***	-0.0044	0.0032		-0.0417	0.0347	

Table 11 Continued

	Large-Cap Stocks			Medium-Cap Stocks			Small-Cap Stocks		
	Coeff.	**Std. Err.**		**Coeff.**	**Std. Err.**		**Coeff.**	**Std. Err.**	
Panel B: LOB sell slope									
Intercept	0.0011	0.0020		0.0153	0.0037	***	0.7459	0.0237	***
D_{HFT}	0.0157	0.0006	***	0.0694	0.0018	***	0.4031	0.0090	***
Resi_OI_lag1	-0.0371	0.0033	***	-0.0555	0.0080	***	-0.0721	0.0316	*
Resi_OI_lag2	-0.0256	0.0035	***	-0.0502	0.0079	***	-0.0533	0.0223	*
Resi_OI_lag3	-0.0186	0.0027	***	-0.0463	0.0078	***	-0.0366	0.0190	
Resi_OI_lag4	-0.0216	0.0021	***	-0.0410	0.0073	***	-0.0173	0.0088	*
Resi_OI_lag5	-0.0211	0.0033	***	-0.0385	0.0072	***	-0.0045	0.0090	
Resi_OI_lag6	-0.0155	0.0016	***	-0.0304	0.0072	***	-0.0078	0.0089	
Resi_OI_lag7	-0.0128	0.0018	***	-0.0298	0.0063	***	-0.0079	0.0139	
Resi_OI_lag8	-0.0116	0.0016	***	-0.0271	0.0064	***	-0.0113	0.0132	
Resi_OI_lag9	-0.0109	0.0011	***	-0.0328	0.0074	***	0.0063	0.0214	
Resi_OI_lag10	-0.0106	0.0012	***	-0.0188	0.0043	***	0.0077	0.0198	
D_{HFT} *x Resi_OI_lag1*	-0.0004	0.0034		0.0303	0.0083	***	0.0668	0.0373	
D_{HFT} *x Resi_OI_lag2*	0.0007	0.0036		0.0303	0.0082	***	0.0489	0.0295	
D_{HFT} *x Resi_OI_lag3*	0.0018	0.0028		0.0329	0.0080	***	0.0362	0.0260	
D_{HFT} *x Resi_OI_lag4*	0.0094	0.0023	***	0.0292	0.0075	***	0.0225	0.0168	
D_{HFT} *x Resi_OI_lag5*	0.0114	0.0034	***	0.0250	0.0074	***	0.0076	0.0130	
D_{HFT} *x Resi_OI_lag6*	0.0079	0.0017	***	0.0193	0.0075	**	0.0073	0.0136	
D_{HFT} *x Resi_OI_lag7*	0.0052	0.0019	**	0.0189	0.0065	**	0.0181	0.0171	
D_{HFT} *x Resi_OI_lag8*	0.0053	0.0017	**	0.0169	0.0065	**	0.0168	0.0157	
D_{HFT} *x Resi_OI_lag9*	0.0043	0.0012	***	0.0234	0.0075	**	-0.0059	0.0231	
D_{HFT} *x Resi_OI_lag10*	0.0045	0.0014	**	0.0107	0.0045	*	0.0024	0.0219	

Appendices

Appendix 1: Sample Stocks

Table A.1 Sample stocks

List of 116 securities in the final sample and their respective market capitalizations on January 3, 2011 (billions).

Ticker Symbol	Market Cap. (billions)	Firm Name	Ticker Symbol	Market Cap. (billions)	Firm Name
AA	16.14	Alcoa Inc.	CKH	2.199	SEACOR Holdings Inc.
AAPL	302.3	Apple Inc.	CMCSA	46.30	Comcast Corp. (Cl A)
ABD	0.485	ACCO Brands Corp.	CNQR	2.768	Concur Technologies Inc.
ADBE	15.92	Adobe Systems Inc.	COO	2.606	Cooper Cos.
AGN	21.36	Allergan Inc.	COST	31.33	Costco Wholesale Corp.
AINV	2.200	Apollo Investment Corp.	CPSI	0.512	Computer Programs & Systems Inc.
AMAT	18.79	Applied Materials Inc.	CPWR	2.571	Compuware Corp.
AMED	1.013	Amedisys Inc.	CR	2.452	Crane Co.
AMGN	52.48	Amgen Inc.	CRI	1.681	Carter's Inc.
AMZN	82.68	Amazon.com Inc.	CRVL	0.584	Corvel Corp.
ANGO	0.390	AngioDynamics Inc.	CSCO	113.6	Cisco Systems Inc.
APOG	0.394	Apogee Enterprises Inc.	CSE	2.318	CapitalSource Inc.
ARCC	3.451	Ares Capital Corp.	CSL	2.469	Carlisle Cos.
AXP	52.24	American Express Co.	CTRN	0.367	Citi Trends Inc.
AYI	2.556	Acuity Brands Inc.	CTSH	22.87	Cognizant Technology Solutions Corp.
AZZ	0.510	AZZ Inc.	DCOM	0.525	Dime Community Bancshares
BAS	0.693	Basic Energy Services Inc.	DELL	26.62	Dell Inc.
BHI	24.71	Baker Hughes Inc.	DIS	71.62	Walt Disney Co.
BIIB	16.01	Biogen Idec Inc.	DK	0.402	Delek US Holdings Inc.
BRCM	20.19	Broadcom Corp.	DOW	40.60	Dow Chemical Co.
BRE	2.822	BRE Properties Inc.	EBAY	37.39	eBay Inc.
BXS	1.378	BancorpSouth Inc.	EBF	0.452	Ennis Inc.
BZ	0.687	Boise Inc.	ERIE	3.383	Erie Indemnity Co. (Cl A)
CB	18.37	Chubb Corp.	ESRX	29.63	Express Scripts Inc.
CBEY	0.478	Cbeyond Inc.	EWBC	2.920	East West Bancorp Inc.
CBT	2.558	Cabot Corp.	FCN	1.700	FTI Consulting Inc.
CBZ	0.313	CBIZ Inc.	FFIC	0.451	Flushing Financial Corp.
CCO	0.600	Clear Channel Outdoor Holdings Inc.	FL	3.062	Foot Locker Inc.
CDR	0.433	Cedar Shopping Centers Inc.	FMER	2.210	FirstMerit Corp.
CELG	28.25	Celgene Corp.	FPO	0.658	First Potomac Realty Trust
CETV	1.205	Central European Media Enterprises Ltd.	FRED	0.553	Fred's Inc.

Table A.1 Continued

Ticker Symbol	Market Cap. (billions)	Firm Name	Ticker Symbol	Market Cap. (billions)	Firm Name
FULT	2.083	Fulton Financial Corp.	MFB	0.574	Maidenform Brands Inc.
GAS	2.294	Nicor Inc.	MIG	0.553	Meadowbrook Insurance Group Inc.
GE	195.4	General Electric Co.	MMM	62.04	3M Co.
GENZ	18.59	Genzyme Corp.	MOD	0.801	Modine Manufacturing Co.
GILD	29.70	Gilead Sciences Inc.	MOS	33.98	Mosaic Co.
GLW	29.99	Corning Inc.	MRTN	0.480	Marten Transport Ltd.
GOOG	150.1	Google Inc. (Cl A)	MXWL	0.509	Maxwell Technologies Inc.
GPS	13.65	Gap Inc.	NC	0.743	NACCO Industries Inc. (Cl A)
HON	42.29	Honeywell International Inc.	NSR	1.945	NeuStar Inc. (Cl A)
HPQ	93.62	Hewlett-Packard Co.	NUS	1.894	Nu Skin Enterprises Inc. (Cl A)
IMGN	0.654	Immunogen Inc.	NXTM	1.238	NxStage Medical Inc.
INTC	116.3	Intel Corp.	PBH	0.593	Prestige Brands Holdings Inc.
IPAR	0.585	Inter Parfums Inc.	PFE	141.6	Pfizer Inc.
ISIL	1.824	Intersil Corp. (Cl A)	PG	183.8	Procter & Gamble Co.
ISRG	10.57	Intuitive Surgical Inc.	PNC	32.32	PNC Financial Services Group Inc.
JKHY	2.534	Jack Henry & Associates Inc.	PNY	2.039	Piedmont Natural Gas Co.
KMB	25.54	Kimberly-Clark Corp.	PPD	0.610	Pre-Paid Legal Services Inc.
KNOL	0.592	Knology Inc.	PTP	1.776	Platinum Underwriters Holdings Ltd.
KR	14.00	Kroger Co.	RIGL	0.402	Rigel Pharmaceuticals Inc.
LANC	1.616	Lancaster Colony Corp.	ROC	3.070	Rockwood Holdings Inc.
LECO	2.820	Lincoln Electric Holdings Inc.	ROCK	0.423	Gibraltar Industries Inc.
LPNT	1.968	Lifepoint Hospitals Inc.	ROG	0.633	Rogers Corp.
LSTR	2.028	Landstar System Inc.	RVI	0.802	Retail Ventures Inc.
MAKO	0.591	MAKO Surgical Corp.	SF	2.217	Stifel Financial Corp.
MANT	0.963	ManTech International Corp. (Cl A)	SFG	2.136	StanCorp Financial Group Inc.
MDCO	0.768	Medicines Co.	SJW	0.489	SJW Corp.
MELI	3.094	MercadoLibre Inc.	SWN	13.20	Southwestern Energy Co.

Appendix 2: Limit Order Addition, Cancellation and Execution by Market Capitalization

Table A.2: Limit order addition, cancellation and execution by market capitalization

This table reports the limit order volume cancelled and submitted by HFT and non-HFT firms for each stock market capitalization group. The construction of this table is similar to that of Table 1. *, **, and *** indicate statistical significance at 0.05, 0.01, and 0.001 levels, respectively.

	Top 3		Top 4 - 10		Top 11 - 20		All Top 50 Levels	
	Mean	**Std.**	**Mean**	**Std.**	**Mean**	**Std.**	**Mean**	**Std.**
Section 1: Large-cap stocks								
Order addition (shares)								
HFT	176932	278141	39643	80577	6100	32354	225276	360268
Non-HFT	305745	3337019	134742	149002	28804	47965	487022	3358491
Order cancellation (shares)								
HFT	164033	253897	38969	81786	6668	33195	212641	340670
Non-HFT	287753	3331651	125513	131129	29269	42321	459733	3349165
Cancellation ratio								
HFT	0.4863	0.0199	0.4935	0.0712	0.5881	0.2384	0.4876	0.0154
Non-HFT	0.4894	0.0323	0.4883	0.0527	0.5288	0.1228	0.4880	0.0191
HFT - non-HFT	-0.0031	***					-0.0004	***
Execution ratio								
HFT	0.0634	0.0506					0.0493	0.0411
Non-HFT	0.0897	0.0748					0.0435	0.0352
HFT - non-HFT	-0.0263	***					0.0058	***
Section 2: Medium-cap stocks								
Order addition (shares)								
HFT	13863	26355	3412	5880	680	2120	18228	31518
Non-HFT	50010	2867757	16895	45411	8748	27623	82839	2870873
Order cancellation (shares)								
HFT	13194	25388	3399	5684	675	1977	17545	30533
Non-HFT	48165	2867464	15998	43310	8341	26795	79582	2870590
Cancellation ratio								
HFT	0.4878	0.0564	0.5200	0.1202	0.5417	0.2727	0.4920	0.0355
Non-HFT	0.4860	0.0390	0.5126	0.1045	0.5190	0.1387	0.4920	0.0293
HFT - non-HFT	0.0019	***					0.0000	
Execution ratio								
HFT	0.0452	0.2910					0.0303	0.1467
Non-HFT	0.0594	0.0715					0.0275	0.0353
HFT - non-HFT	-0.0142	***					0.0028	***

Table A.2 Continued

	Top 3		Top 4 - 10		Top 11 - 20		All Top 50 Levels	
	Mean	**Std.**	**Mean**	**Std.**	**Mean**	**Std.**	**Mean**	**Std.**
Section 3: Small-cap stocks								
Order addition (shares)								
HFT	4096	21722	1477	2945	350	1150	5967	23452
Non-HFT	15332	83409	4568	18969	4794	12907	26293	94805
Order cancellation (shares)								
HFT	3924	21577	1450	2787	346	1038	5763	23247
Non-HFT	14363	74004	4805	21397	4373	12271	25157	93899
Cancellation ratio								
HFT	0.4840	0.1149	0.5325	0.1763	0.5460	0.2619	0.4919	0.0782
Non-HFT	0.4816	0.0566	0.5432	0.1766	0.5178	0.1886	0.4916	0.0479
HFT - non-HFT	0.0025	***					0.0003	***
Execution ratio								
HFT	0.0470	0.2538					0.0256	0.1485
Non-HFT	0.0678	0.3183					0.0354	0.2927
HFT - non-HFT	-0.0207	***					-0.0098	***

As the Table A.2 demonstrates, our sample of HFT firms contributes about 21% (small-cap stocks) to 37% (large cap stocks) of total limit orders to the LOB, and the percentage of total limit orders they cancel exhibits a similar pattern. Interestingly, for both HFT firms and non-HFT firms, their respective order cancellation ratios are relatively stable across stocks of different market capitalizations. The order execution ratio is higher for large-cap stocks than for medium- and small-cap stocks. For large-cap stocks, the order cancellation ratios of HFT firms are lower than those of non-HFT firms, but the difference is economically small. The order execution ratio of HFT firms for orders at the top three price levels of the LOB is smaller than that of non-HFT firms; however, when we include all orders for the top 50 price levels, the order execution ratios are similar. The results for medium- and small-cap stocks also indicate that both firms have similar order cancellation and order execution ratios. These results are consistent with those reported in Table 1.

Appendix 3: Intraday Net Liquidity Provision

Figure A.1: Intraday net liquidity provision

This figure depicts the intraday patterns of net liquidity provision of HFT and non-HFT firms on the Nasdaq markets for a sample of 116 stocks listed on the Nasdaq and NYSE during the first quarter of 2011. The sample stocks are sorted by their market capitalizations on January 3, 2011, and divided into large (top 40 stocks), medium (medium 40 stocks), and small (final 36 stocks) size groups. Twenty-six HFT firms are identified traders and the rest are as non-HFT firms. Limit orders submitted and cancelled are aggregated for each 15-minute interval of the trading day. The net liquidity provision is the difference between total limit order volume submitted and total limit order volume cancelled during each time interval. For each time interval, the figure shows the average net liquidity provision of HFT and non-HFT firms as a percentage of their total daily average net liquidity provision.